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AIR FORCE GROUNDWATER CONTAMINATION CLEANUP: AN EVALUATION OF THE PUMP-AND-TREAT METHOD

THESIS

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Air Force Groundwater Contamination Cleanup: An Evaluation of the Pump-and-Treat Method

THESIS

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Richard P. Ammons

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Abstract

This thesis is an attempt to determine the effectiveness of the Air Force's use of pump-and-treat technology to remediate groundwater contamination. The study is divided into four major sections: 1) literature survey of groundwater contamination problems and remediation technology. 2) identification of bases where pump-and-treat technology has been employed. 3) collection of quantitative data from bases for analysis. 4) analysis of data and recommendations.

Data was obtained from three Air Force installations, McClellan AFB, Wright-Patterson AFB, and Wurtsmith AFB. During remediation, contaminants in most cases show a significant decrease in concentration though levels are still well above regulatory agency requirements. Furthermore, it was found that the inconsistent timing of data sampling and the lack of standardized data storage procedures prevents reliable determination of remediation effectiveness.

Conclusions of this study are that a standardized data collection system be created, under direct supervision of an air staff office, and that a centralized procedure be identified for evaluating the effectiveness of pump-and-treat programs. While the current remediation programs using pump-and-treat initially show large reductions in contaminant concentrations, continued application of this method produces

only slight incremental improvements. It appears that decades may be required to meet existing regulatory limits.

AIR FORCE GROUNDWATER CONTAMINATION CLEANUP: AN EVALUATION OF THE PUMP-AND-TREAT METHOD

I. Introduction

Since the early 1970's, the number of incidents involving groundwater contamination has increased and now poses a serious drain on the limited financial resources available to combat groundwater pollution. "Over the past several years the public has become increasingly more aware of the value and the vulnerability of groundwater resources" (31:757). Furthermore, daily newspapers often carry articles reflecting the deep concern of federal and state environmental agencies over groundwater contamination and the time required to permanently clean up contaminated groundwater present beneath many military bases.

Statement of the Problem

The primary problem facing many installation managers today, military and civilian, is how to effectively clean up contaminated groundwater. Both state and local agencies are pressing for remediation now, using proven technology, even though innovative alternative methods might, sometimes, be more effective.

Currently, the most widely used method of groundwater treatment involves pumping contaminated water out of the

ground and treating it before use, returning it to the groundwater table, or discharging to surface water systems. The success, or effectiveness, of this procedure depends greatly on the nature of the contamination and the specific hydrogeological environment. Unfortunately, since pump-and-treat is a proven technology, it is often used indiscriminately. Given the complexity and variety of groundwater contamination scenarios, certain situations may exist where alternative treatment methods or schemes can be better employed, at lower costs, and still meet regulatory requirements for cleanup.

Purpose of the Study

The purpose of this study, therefore, is to determine if the Air Force's use of the pump-and-treat method meets the necessary requirement for groundwater cleanup in a timely and cost effective manner. This paper attempts to analyze the Air Force use of the pump-and-treat method in an effort to determine those situations for which it is best suited. Are there certain types of contaminations for which this method does not effectively treat the problem? If this is the case, which sites, if any, are likely candidates for use of alternative methods? In April 1988, a telephone conversation with Lieutenant Mike Elliott, project officier in the environmental branch of the Engineering and Service Center at Tyndall Air Force Base, revealed that the Engineering and Service Center will be forming a working group in the fall of

1988 to develop a manual for implementing alternative methods of remediation (14). This paper attempts to determine the success of present pump-and-treat methods, and to validate the need for alternative methods of treatment. Furthermore, the results of this research may provide insight on how to better employ current methods.

Definitions

To fully understand this paper a basic understanding of certain key terms is required. The following terms are briefly defined:

Pump-and-Treat Method - is a process by which water is extracted from the ground and treated using various physical, chemical, or biological treatments. After treatment, the water is distributed for use, returned to the groundwater, or discharged to a surface water source.

Effectiveness - is the degree to which a selected system accomplishes what it set out to do. In other words, effectiveness is a measure of how well the "right" things were completed. To make this determination the following three criteria must be addressed (40:42):

1. Quality - Were the right things done according to predetermined specifications?
2. Quantity - Were all the right things accomplished?
3. Timeliness - Were the right things done on time?

Organization

The remainder of this chapter is arranged by topic. First, the background of groundwater contamination is used to introduce several factors that contribute to the recent increase in groundwater problems. Next, factors affecting transport and treatment of contaminants in groundwater are discussed to demonstrate the complexity of the problem and the present lack of understanding. In conclusion, the Air Force's current groundwater remediation effort is discussed, along with indications of what direction future action may take.

Background

Problems with groundwater are not totally unexpected, as Shackelford and Cline explain:

> As the complexity of the chemical makeup of consumer products increases, the problems of containing and treating the wastes of modern society continue to grow. As population growth continues, the need for that most basic of all commodities, clean water, increases [39:652].

However, in many cases the "initial identification of groundwater contamination is generally unexpected; that is, there usually is no advance warning that a well or spring which has previously had good quality water is going to show evidence of contamination" (1:3).

There are several factors limiting the detection of groundwater contamination. First, "the number of known chemicals involved in manufacturing approaches 60,000; the

number of by-products is unknown" (39:653). Second, reliable methods for detecting contaminants do not exist. "The lack of adequate survey methods to detect and identify unknown compounds precludes the analysis of 80-90% of the total organic carbon that is contained in water samples" (39:653). Finally, in addition to the vast number of possible contaminants, the very nature of groundwater makes detection difficult. "The complex flow paths which can exist in groundwater systems, the wide variety of contamination sources, and the fact the groundwater flow is not directly observable all contribute to this surprise factor" (1:3).

Contaminant Transport and Treatment

The development and use of accurate groundwater transport modeling plays an important role in evaluating, containing and remedying contamination. Pinder explains in the following passage:

> Because groundwater contaminant transport is neither readily observed nor easily measured, the lay person views it as something approaching the metaphysical. Yet, because of the enormous impact this phenomenon has on the long-term viability of potable water supplies, contaminant transport is of tremendous scientific and practical importance [34:108A].

"However, it is critical to keep in mind that the strength of available models is directly related to the depth of present understanding of the fundamental processes that control the transport and fate of contaminants" (24:384). Most water transport modeling centers on movement within the saturated

zone, that region at or below the water table. In many areas of the country this zone lies several hundred feet below the surface. A large portion of current contamination still remains within the unsaturated region above the water table and is slowly filtering down to the groundwater table. Modeling of transport within the unsaturated region is presently in its infancy. Once the contaminant reaches the saturated zone, many of the factors affecting its movement are better understood.

The dominant factor in the migration of a dissolved contaminant is advection, a process by which solutes are transported by the bulk motion of flowing groundwater. In most cases contaminant movement is very slow and varies with soil composition. Mackay et al, in their article, describe typical rates for groundwater migration for a selected soil type.

> . . . when monitoring wells or small supply wells in sand and gravel aquifers are located hundreds or thousands of meters downgradient of a contaminant source, the average travel time for the groundwater to flow from source to well typically is on the order of decades [24:384].

In addition to advection, a dissolved contaminant spreads as it moves with the groundwater. "Dispersion and spreading during transport result in the dilution of contaminant pulses and the attenuation of concentration peaks" (24:385). At the present time, there seems to be no method to confidently predict the magnitude of dispersion.

Lastly, a vast number of contaminants are adsorbed onto the soil or transformed through chemical and/or biological reaction. Roberts et al, conducted several field studies that show movement of contaminants are retarded by their interaction with the soil (36:408-412). It is important to note that the adsorption of contaminants on soil is one of the factors which degrade the effectiveness of the pump-and-treat method. Pumping removes only that contaminant suspended in water, and does not affect the contaminated soil. As clean water migrates through the contaminated soil it also becomes contaminated. This interaction of soil and contaminant is often responsible for the long cleanup times required. Charbeneau presents two excellent papers on how adsorption and ion exchange affect contaminant transport (6:705). Charbeneau suggests that:

> The movement of many pollutants in the groundwater environment relative to the water movement is controlled by adsorption and ion exchange processes. Such pollutants move toward a production well at a slower speed than groundwater flow because they are retarded by the action of these chemical processes [5:1117].

Treatment methods for removing groundwater contaminants may be categorized as physical, chemical, or biological. "Physical methods most commonly used include gravity separation, air flotation, filtration, centrifugation, vacuum filtration, liquid-liquid extraction, evaporation, and carbon absorption" (48:2). Chemical methods, however, take advantage of chemical oxidation, ion exchange, chemical

pretreatment, and coagulation-precipitation to achieve the desired water quality. "Biological methods include activated sludge and its modification, tricking filters, aeration lagoons, and waste stabilization ponds" (48:3).

Many factors affect the final process selection: the characteristics of the pollutant, the subsurface characteristics, the degree of cleanup required, the projected water use, and the economics involved. The final selection and application of a particular process is normally tied to some form of pumping scheme. As Mackay et al, point out in their article, "Remedial schemes designed to stop or reverse the spread of groundwater contaminants often rely on pumping the contaminated zone to purge it of contaminants" (24:385). Mackay and others further state that ". . . current understanding seems to suggest that remediation based solely on pumping is likely to be a long and expensive undertaking" (24:391).

Air Force Efforts

"The Air Force, due to the very nature of its primary job, has long been engaged in a wide variety of operations dealing with toxic and hazardous materials" (10:C3). During early Air Force investigation and cleanup of contaminated groundwater sites, there was no organized procedure to guide Air Force personnel in remediating groundwater contamination.

> This problem has been recognized by the Department of Defense (DOD), and action has been taken to identify the locations and contents of past disposal sites and to eliminate the hazards to public health in an environmentally responsible manner. The DOD program is called the Installation Restoration Program (IRP) [10:1].

The IRP is a four-phased program, originally consisting of Phase I, Initial Assessment/Records Search; Phase II, Confirmation/Quantification; Phase III, Technology Base Development; and Phase IV, Operations/Remedial Actions. The DOD's IRP program is comparable with the Environmental Protection Agency's (EPA) Superfund cleanup program. Like the Superfund, the remedial actions employed by the Air Force to correct groundwater contamination has relied heavily on some form of pump-and-treat process. Literature suggests that this treatment method has not always proved totally successful and tends to take longer and cost more than desired. A telephone interview with Major Patrick T. Fink, LEEVP (Policy and Assessment Branch, Environmental Division), Headquarters, USAF, Bolling Air Force Base, Washington DC, revealed that the effectiveness of the pump-and-treat method on various types of contamination has not been fully studied (16). The Air Force Engineering and Services Center (AFESC) is currently working on a technical manual that can be used by Major Commands (MAJCOM) and base-level engineering staff in evaluating alternatives to the pump-and-treat method (16). This study attempts to evaluate the progress of current Air

Force pump-and-treat programs in an effort to determine the need for alternative methods of treatment.

Limitations of the Study

One major problem with a topic such as this is its size and complexity. The variety of possible groundwater contaminant scenarios along with the small number of bases presently involved in remedial programs (Phase IV, remedial action phase of the IRP) make statistical analysis of this problem difficult. However, some good management procedures dealing with the initiation and monitoring of groundwater remediation programs may be determined.

A second limitation of this study is the definition of effectiveness. For this paper, effectiveness will be viewed as a relative measure. First, does the method attain the required regulatory standard, and next, how does it compare to other methods in terms of cost and feasibility?

In summary, the problem of groundwater contamination has received major emphasis in recent years. The most often used remedial method involves some form of pump-and-treat process. The uncertainties of groundwater movement and the lack of knowledge concerning levels of contamination contribute to the difficulty of evaluating the effectiveness of any treatment process. Before attempting to develop new methods of groundwater treatment, current technological methods must be studied and recommendations made on their effectiveness. This study is limited to those sites where pump-and-treat

technology is being used to remediate groundwater contamination and will concentrate on the quantitative data produced by periodic water and soil sampling, with hopes of determining the long term effectiveness of the process. Even though comparisons may be made to alternative methods of treatment, neither the methodology for selecting specific treatment methods nor the mechanics of each method will be presented in this study.

Plan of the Study

This chapter has outlined the general environment of groundwater contamination and the Department of Defense role in correcting contamination problems created through routine daily operations. Faced with decreasing resources, current remedial methods must be examined and better technology utilized where needed. The next chapter will explore the vast amounts of published literature dealing in groundwater pollutants, their sources, regulations governing acceptable standards, current cleanup methods, cost considerations, and some of the new technology available. Chapter 3 describes the methodology used for data collection and analysis. The data collected from this research effort is presented in Chapter 4 along with an analysis of the effectiveness of the cleanup for each site. Finally, Chapter 5 details the conclusions of this research effort and makes several recommendations for further study.

II. Literature Review

Effective and economical methods of treating groundwater contamination are essential to insure sufficient resources of clean water to meet our ever-increasing demand. A review of applicable literature suggests five main areas which should be examined to determine the effectiveness of current Air Force groundwater treatment: pollutants and their sources, regulations governing acceptable standards, current cleanup technology, new technologies, and economic considerations.

Pollutants

During the last twenty-five years the number of known pollutants has steadily increased, creating serious problems in designing and selecting effective treatment processes. This portion of the literature review attempts, first, to acquaint the reader with the magnitude of groudwater contamination, and second, to identify a few of the more frequent or persistent harmful contaminants. Operating with limited resources, the Department of Defense is forced, out of necessity, to select methods of treatment that remediate the most serious threats first. Furthermore, since many military installations find themselves treating the same types of contaminants found in the private sector, a review of non-defense studies may help to identify those contaminants posing the greatest threat. Identification of contaminants

is the first major step in selecting an effective treatment process.

As early as 1960, groundwater contamination had received attention. An article published by the American Water Works Association over twenty-five years ago demonstrates early concern over the future quality of groundwater resources.

> Industries and legislative bodies were becoming increasingly aware of the problem, that much work and many precautions were necessary to insure satisfactory conditions of water quality [2:619].

Since those early days, one major concern of many researchers has been to identify the nature of pollutants and their sources. A book by Todd and Mcnulty presents a comprehensive review of groundwater pollution and identifies much of the early research being done in this area (42:80-97). Furthermore, the American Chemical Society's Chemical Abstracts Service (CAS) maintains a computer list of chemical substances reported in most of the scientific literature since 1965.

> As of November 1977, CAS's unique computer registry of chemicals contained 4,039,907 distinct entities. The number of chemicals in the register, moreover, has been growing at an average rate of about 6000 per week [27:162].

Due to the rapid growing number of toxic chemicals, the Environmental Protection Agency (EPA), as part of the Toxic Substance Control Act, was charged with maintaining an inventory of chemical substances used for commercial and industrial purposes (27:162).

Early in 1979, the Environmental Protection Agency (EPA) published a list of 129 "priority pollutants" considered to be of greatest environmental concern to the public (48:17). Subsequently, this list has been reduced to 126 compounds consisting of both organic and inorganic materials. The presence of these compounds, in groundwater, is being confirmed with increased regularity throughout the United States (11:394). Determining which contaminants are found most frequently helps to focus technological development on the contaminants creating the greatest threat.

A research effort conducted by Roberts et al, identified some of the more frequently occurring pollutants of groundwater in the United States, many of which are present beneath military installations. The following extract mentions only a few of the more common:

> The following compounds were listed as examples of widely encountered contaminants of groundwater supplies: Trichloroethene (TCE), carbon tetrachloride, trichloroethene, 1,1,1-trichloroethane and methylene chloride [36:408].

Analysis of groundwater samples, over time, at McClellan Air Force Base, supported Roberts et al's findings. The analysis showed that trichloroethene (TCE) was the contaminant most frequently identified in base water supplies (15:2-17). In this case, TCE is also expected to serve as an indicator for the presents of other volatile organic compounds (15:2-17).

In addition, John Dyksen and Alan Hess support the belief that volatile organic compounds, such as chlorinated

hydrocarbon solvents, are among those elements most frequently occurring in groundwater supplies (11:396). According to their research, of all groundwater samples collected, trichloroethene (TCE), an industrial solvent and degreaser, has been detected most frequently (11:396). Furthermore, according to Paul Roberts, professor of environmental science and engineering at Stanford, "TCE is the most widely occurring groundwater contaminant in the west" (30:5). Roberts' claim is further supported by independent research conducted by Dyksen and Hess. They found that "Of all the groundwater samples collected and analyzed, TCE has been detected most frequently and in the highest concentrations" (11:396). In addition, according to Dyksen and Hess, "Tetrachloroethylene (PCE) ranks second in frequency of occurrence" (11:396). Many of the compounds and frequency of occurrence presented by Dyksen and Hess were obtained from 1981 federal studies conducted by the Council on Environmental Quality, Washington DC (11:396). Since the mission of the United States Air Force requires the use of both of these toxic and hazardous materials, it is expected that bases not yet dealing with contamination will in the near future (15:E-1).

Other contaminants commonly detected at Air Force installations are benzene, mercury, pesticides, polychlorinated biphenyls (PCBs), and Toxaphene. In 1981, Kraybill pointed out that awareness of the presence of both organic

and inorganic contaminants in much of the treated water was growing rapidly(22:370).

> Of the total contaminants in the water supply on a worldwide basis, 2221 organic chemicals have been identified, and of these, about 765 are in drinking water. Of this total group of organic chemicals, 43 are recognized or suspected carcinogens, 56 are mutagenic contaminants, and 18 are carcinogenic promoters [22:370].

In his article "Comparison of Groundwater and Surface Water for Patterns and Levels of Contamination by Toxic Substances", William Page suggests that except for some isolated incidents, much of the scientific literature maintains that compared with surface water, groundwater is relatively uncontaminated (32:1475). Page believes that over-concentration on surface water along with unproven assumptions have lead to this conclusion. Through site investigation in New Jersey, Page concluded that groundwater is at least as contaminated with carcinogenic and toxic substances as surface water in the same region (32:1481). For this reason, military installations need to be concerned with methods used to dispose of base waste waters.

As toxic chemical contamination continues to increase, the need for identifying contaminant sources becomes an important task. First, the Department of Defense must determine the extent to which it's activities contribute to the contamination problem and who within the private sector should share in remediation. However, numerous factors, at a given site, influence the identification of a particular

groundwater contaminant and often final determination may not be possible (15:E-6).

Sources of Contamination

Groundwater contamination is the result of many different activities, some related to the mission of the United States Air Force and some from activities within the private sector. Understanding the complexity of identifying a particular source of contamination helps to explain the difficulty in selecting a suitable treatment method.

For extraction pumping to be effective, the contaminant plume must be well defined (7:iii-2). In many cases, however, groundwater flows beneath several contaminated sites, many unknown, picking up various contaminants from one or more areas before being detected in a specific monitoring well (15:E-6). The difficulty, therefore, becomes identifying the specific source of various contaminants.

"Sources of contaminants have been discussed by many authors, including Todd and McNulty [1976], and include waste disposal, various types of industrial process, and many more" (5:1117). For example, water samples taken from sites in the Niagara Falls, New York area showed high concentrations of a number of toxic chemica' .. According to Elder "hazardous waste disposal sites were the major sources for most of the compounds which were found in the New York area" (13:1237). In the case of McClellan Air Force Base, no definite source has yet been identified for the TCE groundwater contamination

in Area "A" (7:iii-3), and may very well be caused by both on and off base activities.

New technology is another major source of contamination, as the nation seeks new sources of energy to meet increasing needs. For example, experiments in underground coal gasification as an alternative method of energy produces varying degrees of groundwater contamination (41:582). Stuermer and others, "describe in detail the composition of organic constituents that were observed 15 months after completion of coal gasification test" (41:582). The identification of problems involving alternative sources of energy must be considered before adopting that alternative for wide spread application.

Also, many of today's industrial advances require the use of several toxic chemicals during processing, from which many hazardous compounds are the by-products. According to Love and Eilers, industry accounts for much of todays groundwater pollution (23:413). Manufacturers often discard industrial wastes at local landfills, also used for military waste disposal, that eventually leach contaminants into the groundwater. When contamination is detected, identification of those responsible becomes a real problem. Industry also contributes to contamination by accidental discharges, landfill leachates, industrial spills, and leaking storage tanks (23:414).

Similarly, organic contaminants come from individual households through sewer and household septic systems (11:395). Often the source of some contaminants is not obvious because the contamination is the by-product of a larger process and requires special screening to detect (23:414). Love and Eilers provide the following example of a major contaminant whose wide use makes source determination very difficult.

> In general, trichloroethene and related compounds are volatile, nonflammable in air, and have poor solubility in water. These characteristics make them useful solvents; they are widely used in industries and households, on military bases, and even within water treatment plants for cleaning and degreasing [23:415].

Past management practices dealing with used chemicals and toxic by-products are another major source of pollution.

The presence of many hazardous organic compounds may be due to inadequate disposal techniques and accidental generation during treatment processes, such as the generation of chloroform during chlorination (21:170A).

A year-long field study by Schwarzenbach et al supports model predictions that organic chemicals introduced into river water through industrial dumping or accidental spills may eventually contaminate large areas of groundwater (38:472). Furthermore, many contaminants move very rapidly with infiltrating water from rivers to groundwater (38:478).

A more recent problem, however, is due to the present intensifying of land use, both for agricultural and

nonagricultural purposes. Contamination occurs due to the excessive use of fertilizers, disposal of solid wastes, and uncontrolled irrigation runoff (17:339).

It is difficult to list all the possible sources of pollution since almost every activity produces some form of contamination. For example, at one end of the spectrum there are the oil recovery plants that discard acid sludge, a toxic by-product of refining (33:405), while at the other end there is the home auto repair which results in discarded oil being disposed of through normal garbage pickup. Once contamination has occurred, identification of the source becomes a driving factor in selecting the specific cleanup method. To date, the use of some form of pumping is being used, but cleanup is often a long and costly process. Identifying the source of contamination, also, is essential for effectively employing a selected pumping scheme or other alternative remedial effort. This review of some of the possible contaminant sources and the difficulty of identifying specific contaminants to specific sites demonstrates the complexity of choosing an effective treatment.

The following section references some of the regulations used to control and clean up toxic pollutants.

Governing Regulations

The Department of Defense has the problem of operating and evaluating remediation efforts that must satisfy the various federal laws and regulations as well as each of the

different state statutes. Basically, these regulations define the standards for which remedial efforts must be designed. This section is intended to review a few of the many federal regulations, many of which are further defined by other state and local legislation.

> Existing legislation to control and regulate the entry of hazardous chemicals into the environment includes the Safe Drinking Water Act (SDWA), the Clean Water Act (CWA), the Toxic Substance Control Act (TSCA), and the Resource Conservation and Recovery Act (RCRA) [21:170A].

"While the primary statutory authority is the Federal Water Pollution Control Act Amendments, several other federal laws may be called upon to protect the water environment" (3:154). An article by Barrett examines the following statutes (3:154):

1. Federal Water Pollution Control Acts.
2. Marine Protection, Research, and Sanctuaries Act.
3. Safe Drinking Water Act.
4. Resource Conservation and Recovery Act.
5. Hazardous Materials Transportation Act.
6. Ports and Waterways Safety Act.
7. Toxic Substance Control Act.
8. Atomic Energy Act.
9. Federal Insecticide, Fungicide, and Rodenticide Act.
10. The Comprehensive Environmental Response, Compensation, and Liability Act (not covered in Barrett's article).

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), commonly known as

"Superfund", established the National Priorities List (NPL) as a vehicle to prioritize funding for various contaminated sites (10:C-16). The Superfund program provided EPA with $1.6 billion to remove hazardous substances, clean up contaminated groundwater, or initiate legal action to secure cleanup or cost recovery of responsible parties (44:2). In 1986 the Superfund Amendment and Reauthorization Act (SARA) was passed to provide an additional $8.5 Billion to clean up priority contamination sites (44:2).

These regulations are all designed to impact control of toxic chemicals. In Barrett's article, "it is suggested that the weakest areas in the control of toxic pollutants are from accidental spills, and from non-point sources such as urban runoff" (3:154). Dealing with these incidents depends on the state of current technology, management techniques, and future developments.

Current Technology

A variety of potential control measures are available for groundwater remediation and each is dependent on the physical, chemical and mass transfer characteristics of both the contaminants and the soil matrix within the aquifer (29:2-1). In order to effectively employ a particular control measure, the characteristics of contaminant transport need to be better understood. As Dagan points out, mathematical modeling of groundwater flow may help to provide

needed information on the migration of contaminants, and more effective uses of current remediation methods (9:813).

The advances in computer technology have significantly increased the level of understanding concerning factors affecting contaminant transport. Furthermore, several good "computer programs have been developed for analysis of one-dimensional multicomponent contaminant transport by Rubin and James, and Lake and Helfferich" (5:1117). Even with the aid of advanced computer models the "prediction of contaminant concentrations movement is a complex problem involving nonuniform flow field hydraulics, dispersion, and chemistry" (5:1117). Furthermore, wide areas of country, especially the Southwest, exist where transport modeling of groundwater flow caused by pumping is inaccurate (19:350A). In areas of the Southwest, the vadose zone, the unsaturated zone between the surface and the water table, is sometimes several hundred feet thick (19:350A). Many of the contaminants, in this region, are found within the vadose zone and pumping is not an effective means of removing the contaminants. Bases located in this area may need to examine other methods of contaminant remediation.

Basically groundwater control measures are implemented to eliminate or retard the migration of hazardous materials that have been released into the groundwater. During a review of aquifer restoration techniques Josephson critically

assessed the following three alternatives for dealing with a contaminated aquifer:

> Forbid use of the aquifer and obtain alternative water supplies, attempt to rehabilitate it, or continue to use the aquifer, but treat the water to remove the contaminants [19:347A].

To assist in option selection, the Environmental Protection Agency recently published a handbook which places remedial technologies for controlling groundwater contamination problems into one of four categories.

> The following technologies can be used singularly or in combination to control groundwater contamination: (1) groundwater pumping, involving extraction of water from or injection of water into wells to capture a plume or alter the direction of groundwater movement; (2) subsurface drains, consisting of gravity collection systems designed to intercept groundwater; (3) low permeability barriers, consisting of a vertical wall of low permeability materials constructed underground to divert groundwater flow or minimize leachate generation and plume movement; or (4) in-situ treatment methods to biologically or chemically remove or attenuate contaminants in the subsurface [43:5-1].

Josephson points out, however, that regardless of which option is selected the restoration of many aquifers will require major scientific and technological efforts, and outlays of funds (19:347A). For the purpose of this study only those control measures which provide for contaminant removal, or contain the movement of contaminated groundwater will be examined.

Currently, "groundwater pumping is commonly employed for contaminated groundwater remediation" (29:2-5). The pumping of contaminated water to the surface for treatment, through one or more extraction wells, is a reliable and cost-

effective remedial action that offers significant benefits (29:2-5). Furthermore, the hydrological gradients created by pumping provides an effective way of preventing a contaminant plume from spreading (29:2-1).

Many direct treatment technologies exist for use in groundwater treatment plants that separate the volatile organic chemicals from pumped groundwater. "These separation technologies include: activated carbon adsorption, air stripping, steam stripping, and steam distillation" (29:2-4).

O'Brien of Calgon Carbon Corporation explains that granular activated carbon is frequently used for treatment of organic chemical contamination, such as carbon tetrachloride and trichloroethene (19:349A). A three year study conducted in Florida, also, showed that granular activated carbon removed about 78% of purgeable halogenated organic compounds (industrial and agricultural pollutants) present in pumped groundwater (47:674). However, waste by-products are generated and measures must be taken to safely dispose of the hazardous wastes. The preferred method of disposal is thermal regeneration or incineration (29:2-3).

Air stripping is among the more frequent methods being used to remove volatile contaminants from groundwater. The method was primarily developed to remove TCE from groundwater but is applicable for many other volatile contaminants (25:9). However, the method does not eliminate the contaminant totally, it merely transfers it from aqueous

solution to the air (25:9). Other processes, like incineration, may need to be added if air quality is also an issue.

Where practical, containment can restrict the spread of subsurface contamination from one area to another. Spread can be controlled by pumping or the use of physical barriers. When soil is homogeneous, the use of hydraulic barriers can be effective to prevent the spread of contaminants (12:70). "Physical barriers include slurry trenches, collection trenches, sheet piling and grout curtains" (12:70). Effective depths range from 70 to 200 feet, but the deeper the contamination the more uncertain the costs and effectiveness. Containment techniques are most applicable when there is an impermeable layer to prevent downward migration. Careful study of contamination sites along with proper management of remediation techniques can have substantial impact on total cost of the project (12:71).

New Methods

In the past, "many of the cleanup activities initiated under the original 1980 Superfund legislation, were nonpermanent cleanups designed primarily to contain contamination on-site" (44:4). In 1986, SARA established the requirement for more permanent solutions, which resulted in higher costs due to the uncertainties involved and required the use of new or alternative technologies (44:4).

"Bioreclamation is an emerging in-situ technology for aquifers contaminated with chlorinated hydrocarbons, but

successful full-scale remediation has not been reported to date" (29:2-8). Even though problems exist in the development of this technology it still provides one possible solution for remediating contaminants for which traditional pumping is ineffective. "In some cases, biological treatment can eliminate hazardous compounds by biotransforming them into innocuous forms" (21:170A).

> Microbial metabolic activity can be classified into three main categories: Aerobic respiration, in which oxygen is required as a terminal electron acceptor; anaerobic respiration, in which sulfate or nitrate serves as a terminal electron acceptor; and fermentation, in which the microoraganism rids itself of excess electrons by exuding reduced organic compounds [43:9-2].

"The bioreclamation method that has been most developed and is most feasible for in-situ treatment is one which relies on aerobic (oxygen-requiring) microbial processes" (43:9-2). Many compounds, however, are not removed efficiently by existing biological treatment techniques and further study in this area is needed (21:170A).

A group of Stanford scientists are experimenting with microbes called methanotrophs to remediate certain contaminants, such as TCE, and have succeeded in degrading TCE by thirty percent (30:5). Kobayashi and Rittmann conducted an in-depth evaluation, under the support of the Advanced Environmental Control Technology Research Center at the University of Illinois and the U.S. EPA, of the potential for microorganisms to remove anthropogenic organic compounds, mainly priority pollutants (21:170A).

> The evaluation indicates that the use of properly selected populations of microbes, and the maintenance of environmental conditions most conducive to their metabolism, can be an important means of improving biological treatment of organic wastes (21:170A).

At the present time the Air Force has several field demonstrations underway using the biodegradation process (25:17). This method appears to be useful for treating soil or groundwater contaminated with hydrocarbons such as fuels and fuel oils which result from leaky storage tanks, and fire training pits (25:43). However, a recent technology update on bioremediation produced by Colonel Lawrence D. Hokanson, USAF, Director of the Engineering and Services Laboratory, Tyndall Air Force Base, Florida, concluded that enhanced biodegradation of fuel spills still has serious limitations which could restrict its successful application to relatively few Air Force Bases (18:1). Theoretically, the treatment of contaminants in-situ using biological methods can be accomplished faster than other methods. However, costs associated with this approach appear to be higher than other methods available, and a great deal of research is still required (25:43). Improved pumping methods and development of other in-situ techniques, such as soil venting, may provide effective alternatives while biological research continues.

Economic Considerations

One of the major factors affecting the selection of a particular treatment process is cost. Presently, typical

costs of monitoring wells range from $400 to $3000 each (19:348A). Reducing the number of monitoring wells may be achieved through better understanding of groundwater flow. Kirk Brown suggests that while monitoring wells will always have to be used to delineate groundwater contamination, other less expensive methods might be employed to obtain at least a rough idea of where the wells can most effectively be placed (19:348A). The cost of delineating the contamination plumes, may be reduced if various geophysical monitoring technologies are refined (19:350A). Donald Bruehl of Normandeau Associates Inc. lists electrical resistivity sounding, seismic refraction profiling, and precision gravity surveys as methods providing good results (19:348A).

Schmidt points out that hundreds of thousands of dollars must be spent merely to define a plume. Once a plume is defined, millions of dollars are required to construct facilities, maintain operation, and provide maintenance support for many years (19:350).

Deciding on which remediation method to choose often depends on the availability of funds. O'Brien of Calgon Carbon Corporation estimates that operating costs for granular activated carbon (GAC) is between $0.22 and $2.52 per 1000 gallons treated, depending upon the chemicals and their concentrations (19:349A).

In the case of TCE removal at Wurtsmith AFB, the project cost for air stripping was $0.12 per 1,000 gallons (25:9).

This low cost was primarily due to low maintenance operation and capital investment. The final report on the Sharpe Army Depot pilot test provides an example of typical capital and operating costs for using air stripping technology:

> For the system to handle a TCE flow of 100 gpm with influent and effluent concentrations of 1,500 ug/L and 5 ug/L, respectively, total capital costs were estimated at $71,750 and total annual operating expenses were estimated at $4,300 [25:9].

Assuming a project life of ten years, this is equivalent to a cost of $0.23 per 1000 gallons.

At the present time costs have not been established for biological treatment in-situ, but cost are estimated to range between those for air stripping and carbon adsorption (25:17).

A recent paper presented by Keely examines the merits of using a pulse pumping method to remove those persistent contaminants that continuous pumping fails to reach (20:91). Even though this method incurs certain additional capital investment costs, the advantage of extracting higher levels of contaminant, may make the approach more cost effective (20:99).

This literature review attempted to accomplish three things. First, that Air Force installations are discovering the same types of contaminants found in many metropolitan areas. Second, the process of identifying the source of a particular contaminant is extremely difficult given the complexity of groundwater flow and the vast number of

different contamination scenarios which exist. Lastly, there are numerous state and federal regulations governing the quality of groundwater and several methods of treatment that are available. Each method has advantages and disadvantages depending on specific site conditions and the availability of funds. With all these factors in mind, the following chapters will try to determine if the Air Force is effectively employing pump-and-treat techniques.

III. Methodology

Overview

This research effort is structured to determine if the selection of the pump-and-treat method, for contaminated groundwater at a given site, best suits the needs of the Air Force. A review of current literature indicates that the pump-and-treat technology is often the most widely employed groundwater treatment method because of it's economical advantages and the ability to demonstrate immediate action using available technology (29:2-5). However, in many situations, due to a combination of adverse hydrogeology and contaminant this method may fail to suitably clean up the groundwater. This chapter details the method used to investigate the effectiveness of current pump-and-treat remediation within the Air Force.

Investigative Questions

In order to determine the effectiveness of the pump-and-treat method for groundwater cleanup the following investigative questions need to be answered:

1. In the Air Force, how widely used is the pump-and-treat method of cleanup compared to other methods?
2. What is the Air Force criteria for determination of a successful cleanup process?
3. How successful has the pump-and-treat method been at bases where it has been used?

4. How long is the method employed before acceptable results are obtained?

5. What problems have been encountered using this method of treatment?

Data Collection

This section outlines the intended plan for this research effort. The actual results, analysis, and problems dealing with data collection for this project are presented in chapter IV.

To answer research questions one and two, primary data was gathered from the Policy and Assessment Branch, Environmental Division, Headquarters, USAF/LEEVP, Bolling AFB, Washington, DC. A listing of all the bases currently involved in cleanup action was obtained, along with the type of remedial action and available current costs. This provides the necessary data to apply descriptive statistics. In order to determine the degree to which various methods are employed, the categorical data will be analyzed through use of frequency distributions and histograms. The use of the pump-and-treat method will then be compared to alternative methods currently available.

Next, to assess the degree of success or efficiency of the pump-and-treat method, personnel from the Environics Division of the Engineering and Services laboratory, Engineering and Services Center, Tyndall AFB, were interviewed to establish those factors used to rate progress of remediation efforts. These factors form the basis of the

model that is used to evaluate the effectiveness of the pump-and-treat method. The comparative model will classify current and past treatments into one of three categories.

Category 1: Treatment does not meet minimum EPA requirements for groundwater remediation.

Category 2: Treatment just meets minimum EPA requirements for final groundwater quality.

Category 3: Treatment greatly exceeds minimum EPA requirements for final groundwater quality.

Progress reports obtained from the Major Command and the individual bases are used to place each base treatment into one of the three categories, and to answer research questions 4 and 5. These reports provide data on levels of the contamination prior to the start of treatment as well as improvements made once remediation began.

Analysis/Conclusion

The final step of analysis involves an examination of each of the three categories to determine any characteristic trends, such as, how contaminant source, geography, proximity to populated areas, or extent of groundwater study relate to effectiveness of cleanup. The findings will be presented to the environmental departments of the School of Civil Engineering and Services and the Engineering and Services Center to review for validation. The final goal of this paper is to summarize the findings into a list of site and contaminant characteristics for which the pump-and-treat method is found to be best suited.

The following chapters provide a detailed examination of the Air Force use of the pump-and-treat method. Summaries of research findings along with recommendations for future study are provided in an effort to stimulate further research in this area.

IV. Results and Analysis

Introduction

This chapter presents the research results and provides an analysis of data collected. The objective of this paper was to evaluate all Air Force pump-and-treat projects for effectiveness and to compare them to alternative methods. However, problems in data collection degraded this effort into a case study of three selected cleanup efforts: the McClellan Air Force Base extraction program, the Wright-Patterson Air Force Base fuel spill cleanup, and the Wurtsmith Air Force Base TCE air stripping operation.

Before discussing the results of the three case studies, for which quantitative data was obtained, the extent to which the Air Force uses the pump-and-treat remediation was determined. Telephone interviews with Major Dennis Sullivan, LEEVP, Headquarters, USAF, revealed that very few bases are actively remediating groundwater contamination. Table I lists those bases, during the last four years, that have engaged in active treatment programs or are completing final assessment of proposed action. This table identifies the base, specifies the type of remediation action, and lists the amount funded for each program.

With the exception of biological field test programs, conducted at Eglin Air Force Base and Kelly Air Force Base, all base treatment programs rely on some form of extraction

TABLE I

Air Force Installations Currently Conducting Remediation Programs

LOCATION	DESCRIPTION	AMOUNT OBLIGATED ($000) FY 85 through 88
AF Plant 6	Cleanup Groundwater	3,800
AF PLant 44	Assess Groundwater	4,878
AF Plant 44	Groundwater Monitoring	2,071
AF Plant 44	Cleanup Groundwater	20,600
Castle AFB	Provide TCE Well Filter	48
Castle AFB	TCE Treatment	2,370
Edwards AFB	RAP, Remove Groundwater TCE	301
Edwards AFB	Recover JP-4 From Groundwater	1,362
Edwards AFB	Soil & Groundwater Cleanup	58
Eglin AFB	RAP/Design, Site A20	965
Eglin AFB	RAP/Design, 7th St Station	63
Eglin AFB	Cleanup 7th St Station	979
Eglin AFB	Biodegradation of Fuel (Test)	85
Hickam AFB	Subsurface POL Recovery (14,15)	534
Hickam AFB	Subsurface POL Recovery (13,19)	650
Hill AFB	Emergency Groundwater Treatment	524
Hill AFB	Landfill Treatment 1,2,3,4	1,218
Hill AFB	Remove Oil/Solvent 1,2,3,4	1,258
Holloman AFB	Recover Floating MOGAS	178
Homestead AFB	Purchase POL Recovery Equip	10
Homestead AFB	Remove JP-4 From Groundwater	504
Kelly AFB	Biodegradation of Fuel (Test)	Unknown
Langley AFB	Design Groundwater Fuel Recovery	26
Langley AFB	RAP, Remove JP-4 From Groundwater	358
Langley AFB	Purchase POL Recovery Equip	13
McDill AFB	Fuel Storage Area Cleanup	500
McClellan AFB	Well 18 Carbon Replacement	90
McClellan AFB	Design Modification, Area D	537
McClellan AFB	Groundwater Treatment, Area D	4,736
McClellan AFB	Monitoring/Extraction Wells	549
McClellan AFB	Groundwater Air Modeling Area D	24
Mcguire AFB	Groundwater Cleanup, POL Area	8
Peterson	FLD DEW LINE PCB Removal	67
Sey-Johnson AFB	RAP for POL Recovery	46
Sey-Johnson AFB	Purchase POL Recovery Equip	15
Sey-Johnson AFB	Recovery POL From Groundwater	18
Tyndall AFB	Study Organics Air-Stripping	580
Tyndall AFB	Carbon Adsorp of Air-Stripping	132
Wright-Pat AFB	Cleanup Groundwater	1,141
Wurtsmith AFB	Activated Carbon Replacement	257
Wurtsmith AFB	Benezene Purge Wells	15
Wurtsmith AFB	Install Deep Test Wells	42
Wurtsmith AFB	Design Well 18, Plume	35
Wurtsmith AFB	TCE/DCE Treatment System	684

to remediate groundwater contamination. At Wright-Patterson AFB, however, biodegradation is currently being using to augment groundwater contaminant extraction, in hopes of remediating contaminated soil not affected by pumping.

Nine of the bases listed in Table I were contacted to determine the status of their program and asked to provide progress reports, IRP phase reports, feasibility studies, water sample logs, and any summary reports showing quantitative data on groundwater concentrations. As of this writing, sufficient information for analysis has only been received from McClellan Air Force Base, Wright-Patterson Air Force Base, and Wurtsmith Air Force Base.

Data and analysis of these bases will be presented as case studies, and should not be interpreted as representing the success of operations at other sites. However, these cases do represent current management of remediation systems, and a close examination may provide improved methods of operation, monitoring, and evaluation.

McClellan AFB

Groundwater cleanup at McClellan Air Force Base has been quite extensive and involves four distinct areas (15:4-4). Figure 1 shows the base layout, the four areas of current contamination, and the general location of wells containing elevated levels of contaminants. This case study, however, concentrates only on Area D, since it has received most of the cleanup effort so far.

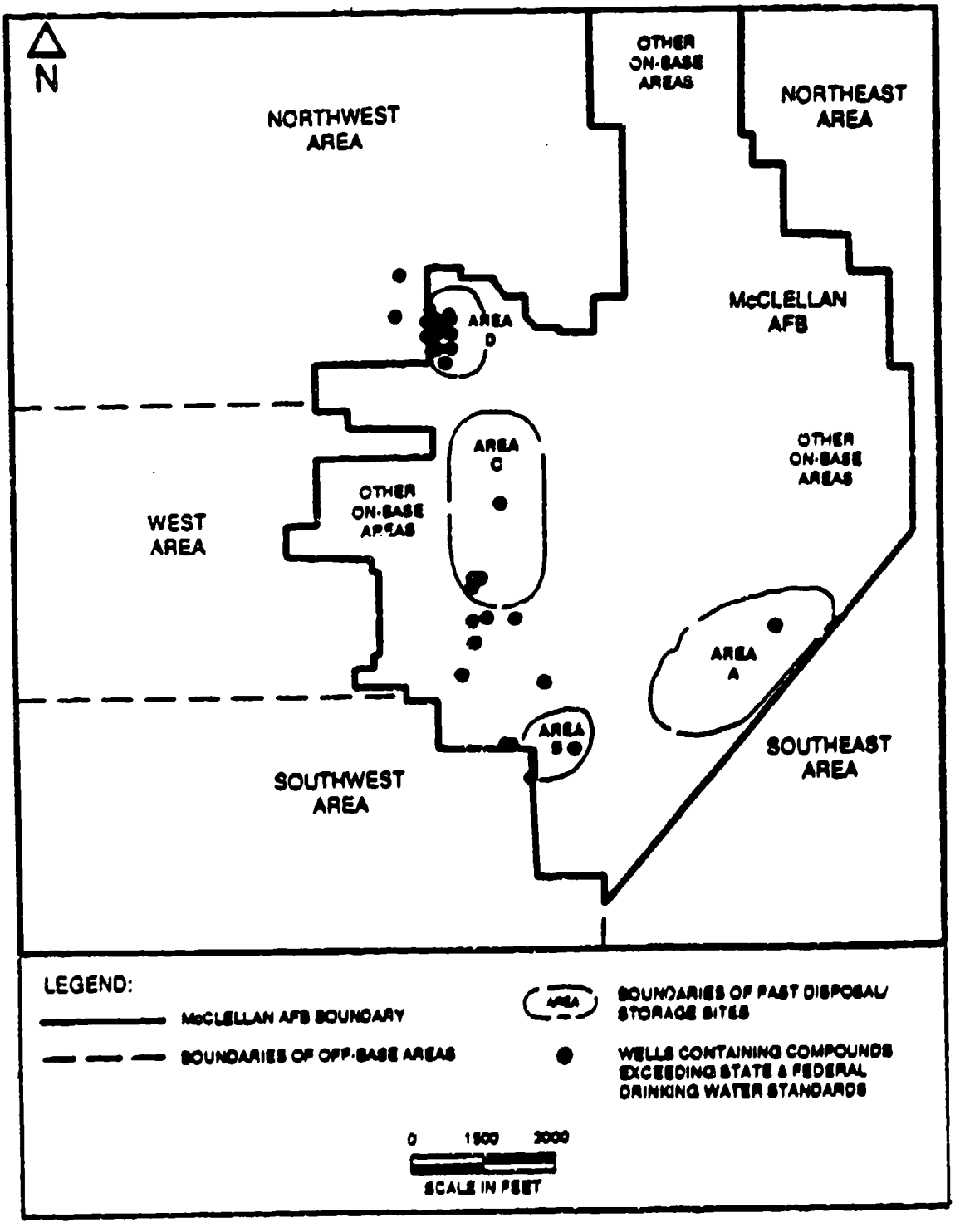

Figure 1. Wells Containing Contaminant Concentrations Exceeding State and Federal Drinking Water Standards, McClellan AFB Second Quarter 1988 Sampling and Analysis Program

The Area D Interim Remedial System is made up of three components that require continuing operation and maintenance or monitoring programs. These components consist of 1) the Area D cap covering the old waste pits (will not be discussed), 2) the groundwater extraction and monitoring system, and 3) a groundwater treatment plant, completed in 1986 at a capital cost of approximately eight million dollars (37:1). The treatment plant has been in operation continuously since March 1987 and is responsible for reducing contaminant concentrations of groundwater pumped from the Area D site, down to a level allowable for discharge to surface waters (37:4).

The current extraction/treatment alternative was selected by a public task force technical review committee, following investigations conducted by CH2M Hill during 1984 through 1985 (37:1). Furthermore, the combined method was selected as being the most technically and financially advantageous for conditions existing at the Area D site (37:1).

The Area D well system consists of forty-one monitoring wells and six extraction wells which vary in depth from 87 to 189 feet (37:2). Static water levels of each well are measured to ensure groundwater containment within Area D and water samples are analyzed to evaluate variations in groundwater contaminant concentrations over time. The annual cost of this analysis program is approximately $114,000 (37:2).

Table II lists the present contaminant level for each well within the Area D system that has concentrations exceeding state and federal Drinking Water Standards; lists the California Department of Health Services (DOHS) minimum action level; and provides the Environmental Protection Agency's (EPA) maximum allowable concentration level.

The Area D extraction system has been in continuous operation since March 1987 at an extraction rate of 100 gallons per minute (gpm) (37:4). The treatment plant incorporates several processes to reduce the pumped groundwater contaminant concentrations down to levels allowable for surface water discharge. The process includes; 1) high temperature air stripping, to remove volatile organic chemicals (VOCs); 2) incineration, to destroy VOCs in the air stripper offgas; 3) carbon filtration, to remove non-volatile organic chemicals; 4) biological treatment, to remove ketones from the groundwater. The annual costs of operating this treatment plant are approximately $900,000 (37:5).

The groundwater contaminant concentration levels, from June 1985 to June 1988, for all monitoring wells sampled at McClellan Air Force Base by the Radian Corporation is provided in Appendix B. The data contained in Appendix B is presently being used by Jerry Robbins, Environmental Coordinator of McClellan Air Force Base, to determine the effectiveness of their program on improving groundwater quality.

Table II

Wells Containing Analytes At Concentrations Exceeding State and Federal Drinking Water Standards, Second Quarter 1988 Sampling and Analysis Program

Well Number	Analyte Detected	Concentration (ug/L) April	May	June	DOHS Action	EPA Standard
EW-73	Vinyl Chloride	1000	2300	1100	2	1
	1,1-Dichloroethene	8200	14000	11000	6	7
	1,1-Dichloroethane	790	690	500	20	NE
	Total 1, 2-Dichloroethene	1400	1400	1000	16	NE
	1,1,1-Trichloroethane	950	2200	1100	200	200
	Trichloroethene	1400	1700	1300	5	5
	Toluene	350	750	790	100	NE
	Tetrachloroethene	-	-	5.7	4	NE
EW-83	1,1-Dichloroethene	610	520	920	6	7
	Trichloroethene	81	66	120	5	5
	Tetrachloroethene	-	-	27	4	NE
EW-84	Vinyl Chloride	330	280	260	2	1
	1,1-Dichloroethene	1100	1100	1600	6	7
	1,1-Dichloroethane	140	210	120	20	NE
	Total 1, 2-Dichloroethene	83	79	110	16	NE
	1,1,1-Trichloroethane	-	-	200	200	200
	Trichloroethene	1300	1200	1100	5	5
	Tetrachloroethene	-	5.7	-	4	NE
	Benzene	-	6.0	-	.7	5
EW-85	1,1-Dichloroethene	1600	1300	2100	6	7
	Total 1, 2-Dichloroethene	28	14	-	16	NE
	1,1,1-Trichloroethane	350	220	390	200	200
	Trichloroethene	1600	1200	1300	5	5
EW-86	1,1-Dichloroethene	120	86	170	6	7
	Trichloroethene	73	52	67	5	5
EW-87	1,1-Dichloroethene	110	65	150	6	7
	Trichloroethene	37	21	42	5	5

Table II (continued)

Well Number	Analyte Detected	Concentration (ug/L) April	May	June	DOHS Action	EPA Standard
MW-10	Vinyl Chloride	400	-	-	2	1
	1,1-Dichloroethene	910	-	-	6	7
	1,1-Dichloroethane	230	-	-	20	NE
	1,2-Dichloroethane	390	-	-	1	5
	Trichloroethene	1500	-	-	5	5
	1,2-Dichlorobenzen	200	-	-	130	NE
	Benzene	11	-	-	.7	5
MW-11	Vinyl Chloride	13	-	-	2	1
	Methylene Chloride	260	-	-	40	NE
	1,1-Dichloroethene	17000	-	-	6	7
	1,1-Dichloroethane	520	-	-	20	NE
	Total 1, 2-Dichloroethene	51	-	-	16	NE
	1,1,1-Trichloroethane	3800	-	-	200	200
	Trichloroethene	6200	-	-	5	5
	Tetrachloroethene	25	-	-	4	NE
	1,4-Dichlorobenzene	2	-	-	.5	NE
	Benzene	30	-	-	.7	5
MW-12	1,1-Dichloroethene	8400	-	-	6	7
	1,1-Dichloroethane	29	-	-	20	NE
	1,1,1-Trichloroethane	1200	-	-	200	200
	Trichloroethene	2500	-	-	5	5
	Tetrachloroethene	200	-	-	4	NE
MW-14	1,1-Dichloroethene	5700	-	-	6	7
	1,1-Dichloroethane	49	-	-	20	NE
	Total 1, 2-Dichloroethene	27	-	-	16	NE
	1,2-Dichloroethane	36	-	-	1	5
	1,1,1-Trichloroethane	3100	-	-	200	200
	Trichloroethene	6500	-	-	5	5
	Tetrachloroethene	7.6	-	-	4	NE
	1,4-Dichlorobenzene	1.4	-	-	.5	NE
MW-15	1,1-Dichloroethene	83	-	-	6	7
	1,1-Dichloroethane	24	-	-	20	NE
	1,2-Dichloroethane	6.8	-	-	1	5
	Trichloroetnene	550	-	-	5	5

Table II (continued)

Well Number	Analyte Detected	Concentration (ug/L) April	May	June	DOHS Action	EPA Standard
MW-55	1,1-Dichloroethene	11	-	-	6	7
MW-72	1,1-Dichloroethene	800	-	-	6	7
	1,1-Dichloroethane	50	-	-	20	NE
	Total 1, 2-Dichloroethene	48	-	-	16	NE
	1,2-Dichloroethane	210	-	-	1	5
MW-141	Total 1, 2-Dichloroethene	60	-	-	16	NE
	Trichloroethene	150	-	-	5	5
MW-1004	1,1-Dichloroethene	14	-	-	5	5
MW-1005	1,1-Dichloroethene	38	-	-	5	5
	1,2-Dichloroethane	1.1	-	-	1	5
	Trichloroethene	12	-	-	5	5

The DOHS action level referenced is the expected limit of quantization for U.S. EPA Methods 601 and 602.

EPA Standard is the minimum concentration allowed by federal regulations.

DOHS Action is the concentration level required by the California Department of Health Services.

MW = Monitoring Wells
EW = Extraction Wells
NE = Not Established

Since beginning the extraction program in March 1987 the sample contaminant concentrations shown in Appendix B indicate that concentrations in most of the monitoring wells have decreased but still remain well above required state and federal standards. Figure 2, extracted from a series of plates provided by the Radian Corporation, shows the middle monitoring zone water level for area D data collected May 2-3, 1988. This plot indicates that the general groundwater gradient is toward the extraction wells. However, because of unknown subsurface interactions, this author believes that the plots alone do not confirm that pumping is effectively drawing contaminants toward the extraction points.

Figure 3 shows the location of most of the monitoring wells for the Area D site along with current (as of June 1988) concentrations of TCE. Comparing the data in Appendix B with the location of the monitoring wells with respect to the extraction wells, it is observed that contaminant concentrations are increasing in some wells near the extraction points. Monitoring wells further away from the extraction point all show decreases. Without knowing the precise plume distribution this would indicate that the main portion of the contaminant plume is moving in the direction of the extraction wells. Whether or not the total of contaminant mass in solution is decreasing or not is impossible to determine from the sampling plan used to collect data. A vast majority of the wells were sampled less

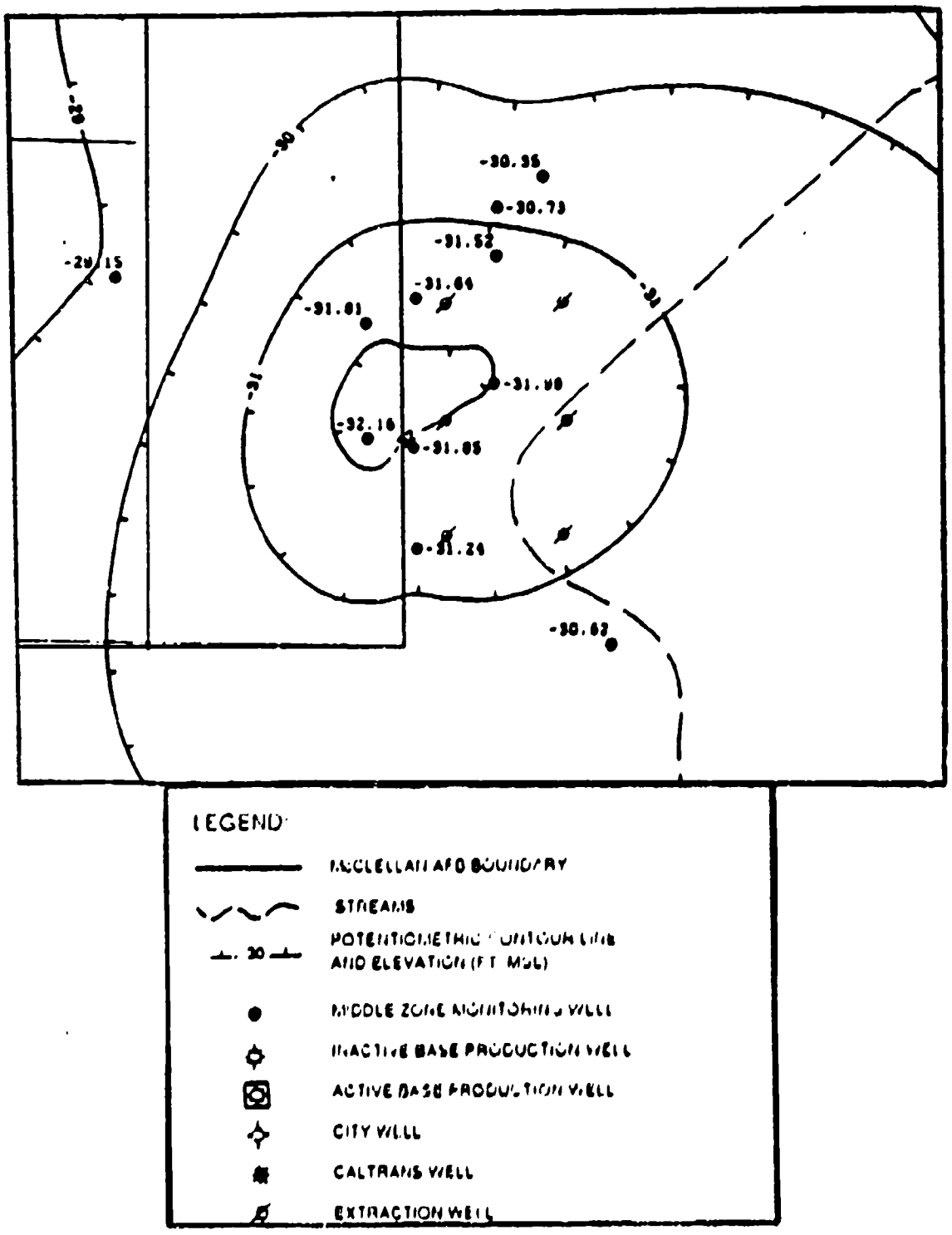

Figure 2. McClellan AFB, Area D - Middle Monitoring Zone Potentiometric Surface Map For Data Collected May 2-3, 1988

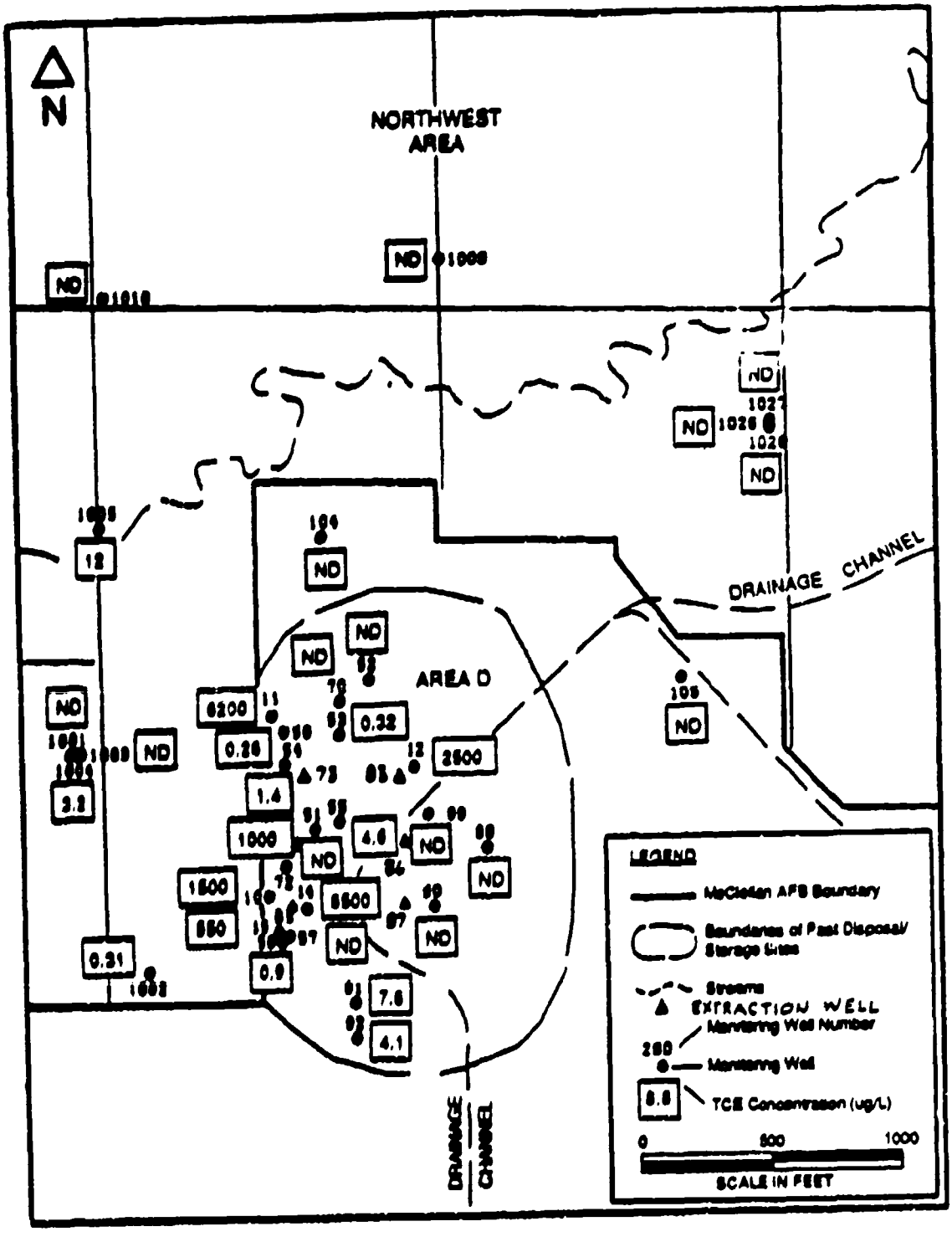

Figure 3. Monitoring Well Location and TCE Concentrations, McClellan AFB Second Quarter 1988 Sampling and Analysis Program

than three times for a particular analyte and others were either not sampled, not in existence, or showed no contamination level. Furthermore, when wells were sampled for a particular analyte they often were sampled at different times. Therefore, the distribution of the plume concentration for a specific time can not be determined. Had samples been taken at regular intervals from all wells, or at least the same wells, a three dimensional plot of the concentrations could be produced. Such a plot could be used to explain the concentration trend for each well sampling curve. Furthermore, the total plume could than be monitored for increases or decreases in total groundwater contamination.

Time series plots of TCE are presented in Figures 4 through 14, as examples of concentration trends within the Area D monitoring system. This contaminant was chosen because it was the most widely sampled analyte that exceeded state and federal standards. Figures 4 through 9 depict concentration trends for monitoring wells located near the extraction wells and have an equal distribution of wells that show increasing or decreasing concentrations levels. Figures 10 through 14 depict decreasing concentration trends for several wells located at varying distances from the extraction wells.

In summary, the McClellan Air Force Base groundwater treatment program indicates that use of the pump-and-treat

Trichloroethene

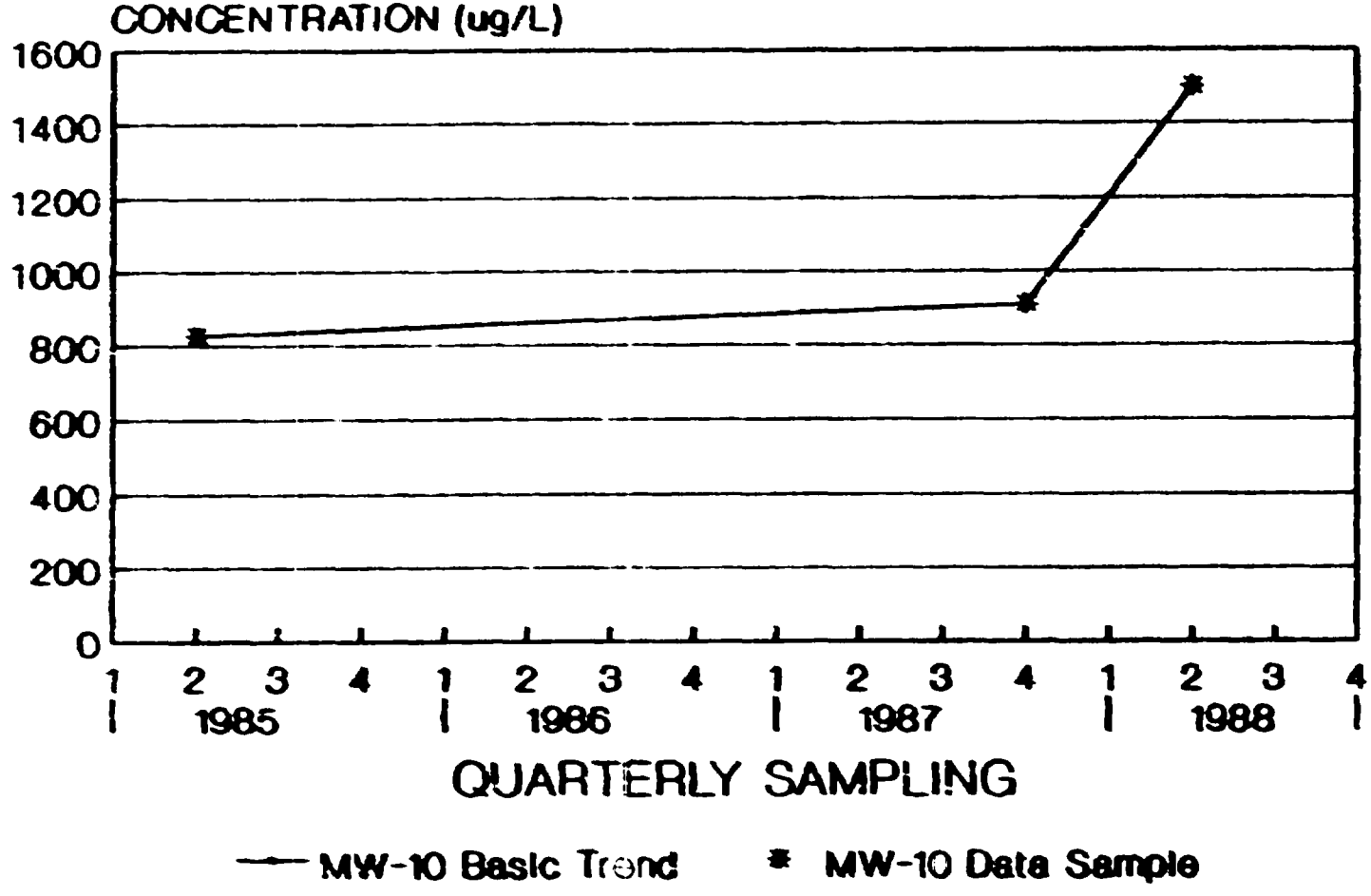

Figure 4. McClellan AFB Well Sampling, Area D

Trichloroethene

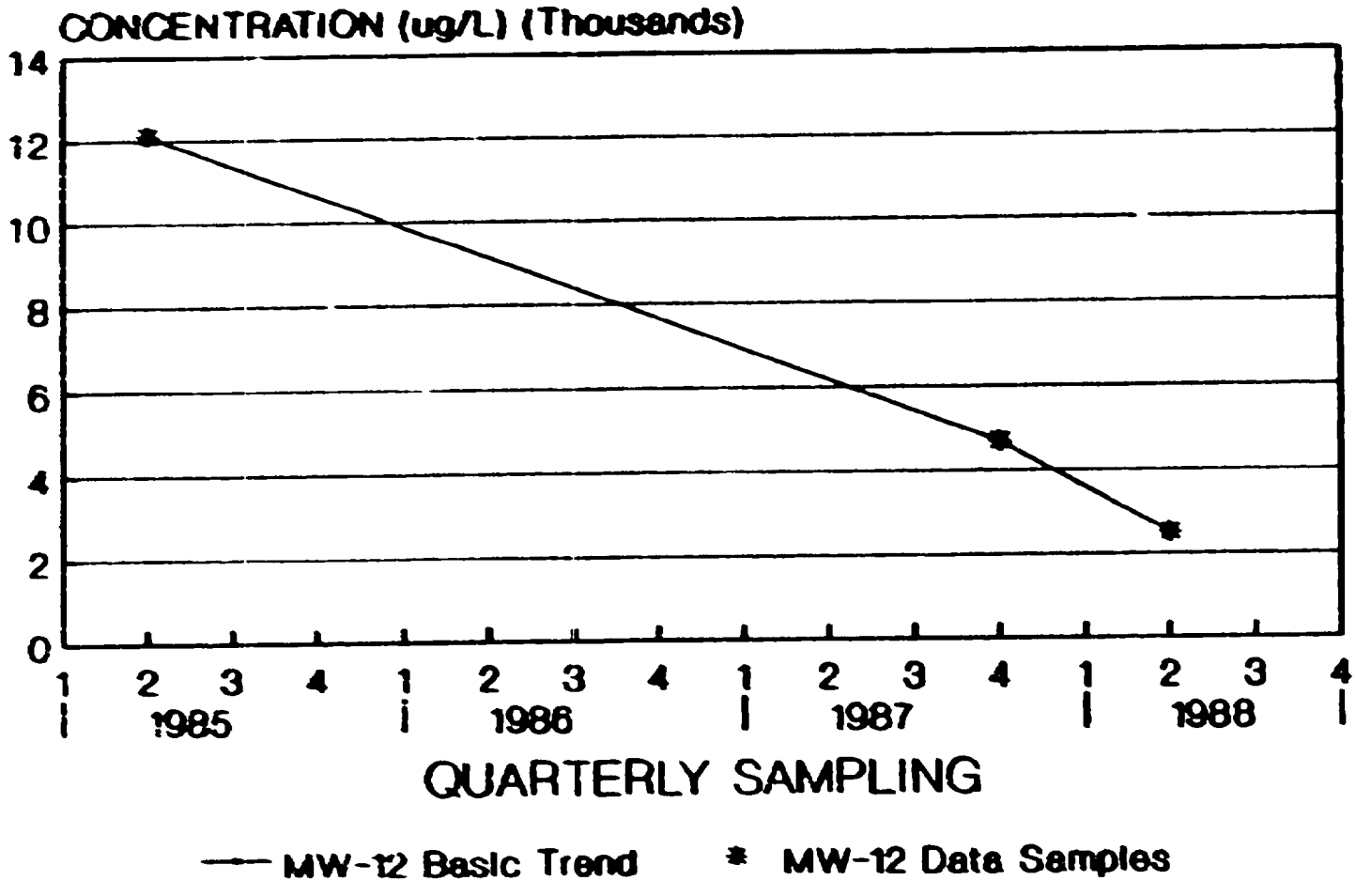

Figure 5. McClellan AFB Well Sampling, Area D

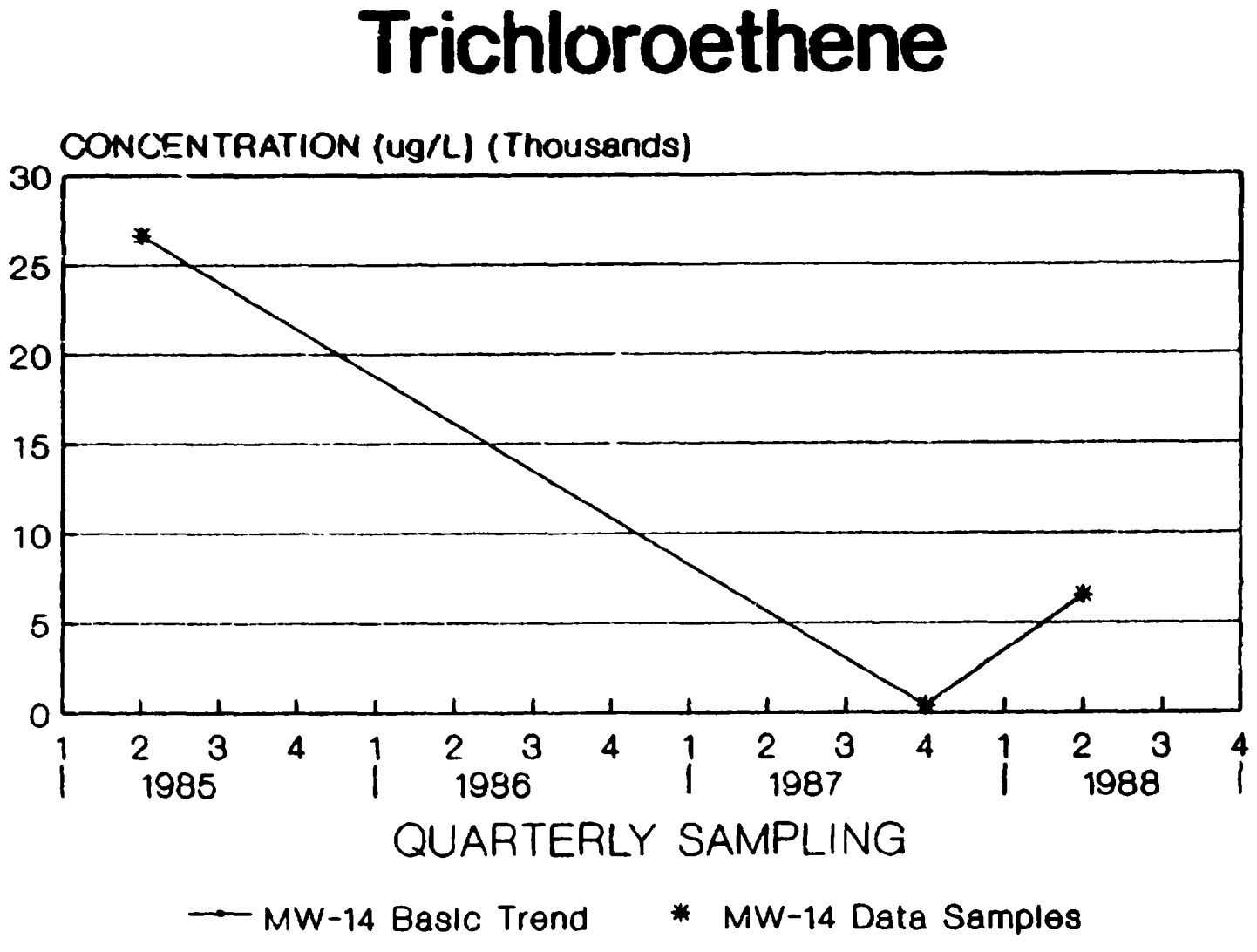

Figure 6. McClellan AFB Well Sampling, Area D

Trichloroethene

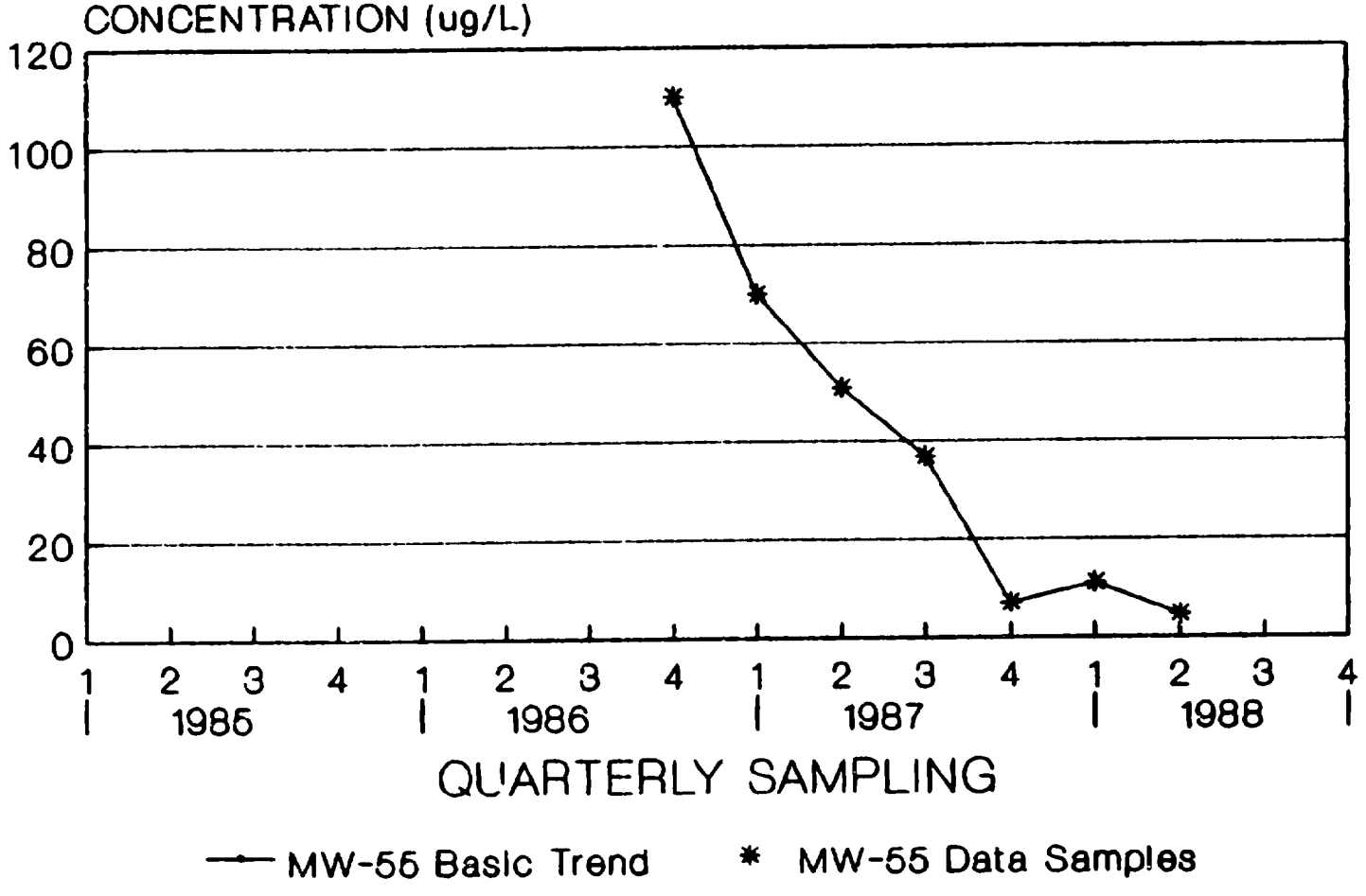

Figure 7. McClellan AFB Well Sampling, Area D

Trichloroethene

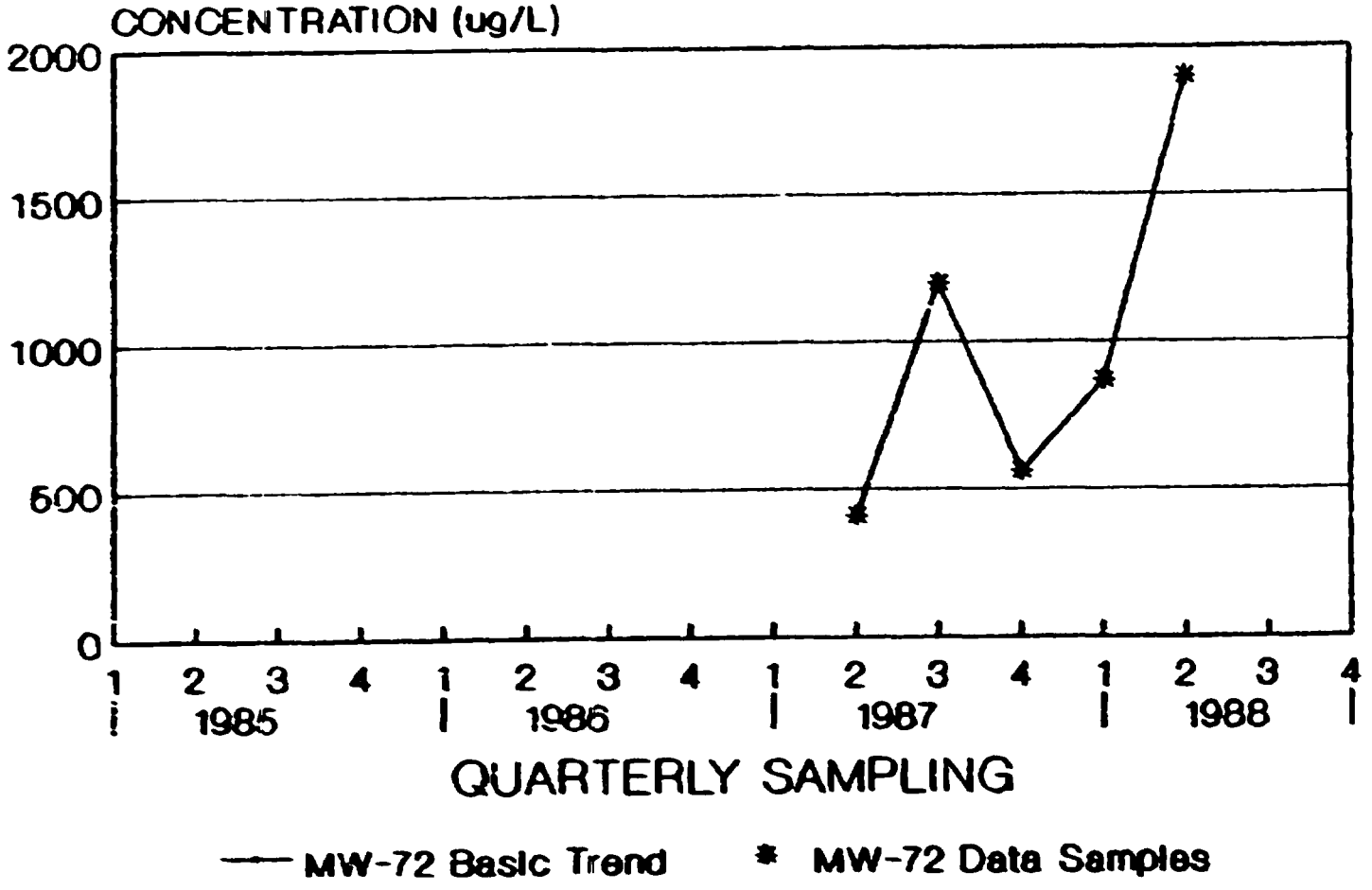

Figure 8. McClellan AFB Well Sampling, Area D

Trichloroethene

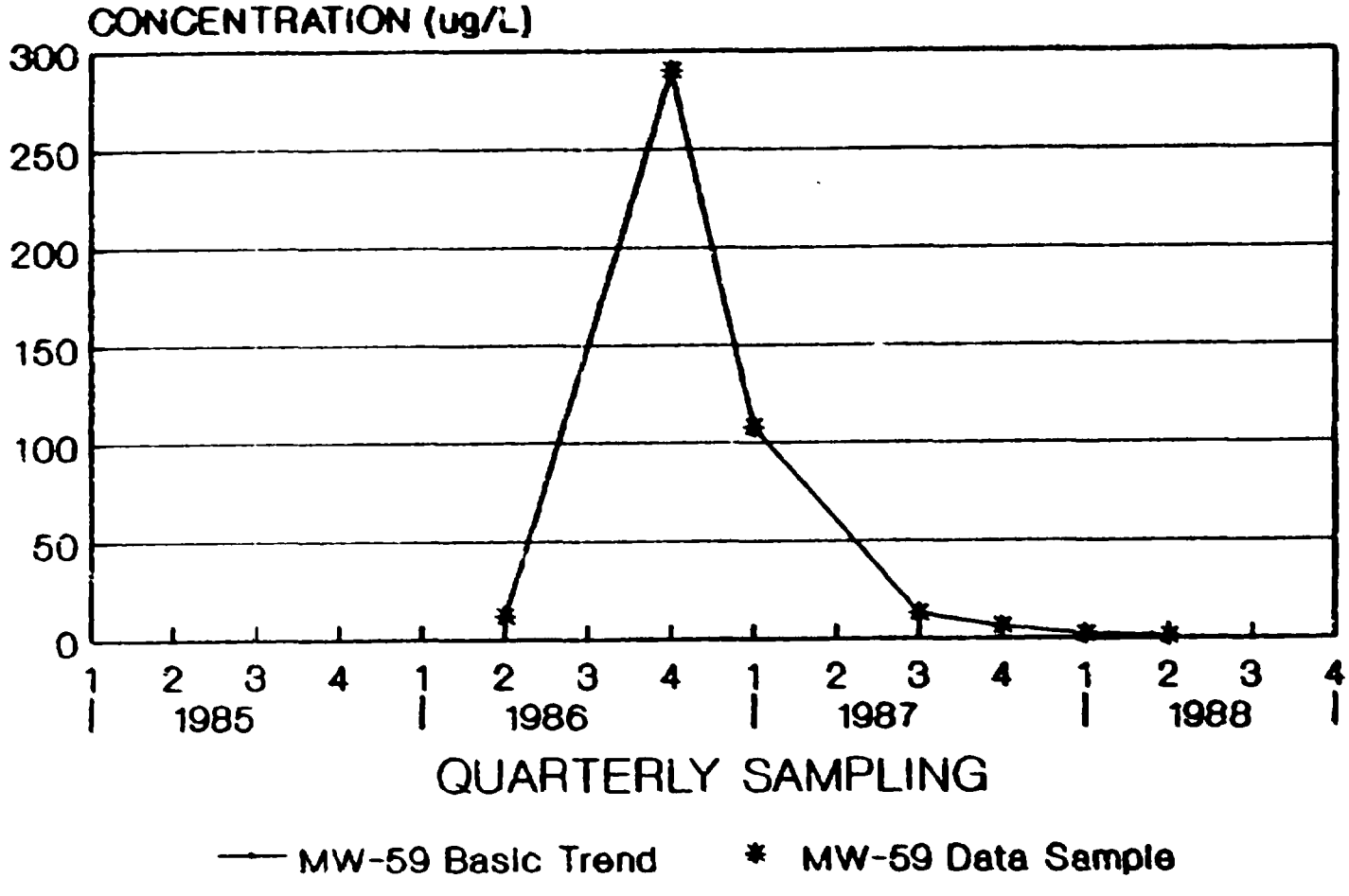

Figure 9. McClellan AFB Well Sampling, Area D

Trichloroethene

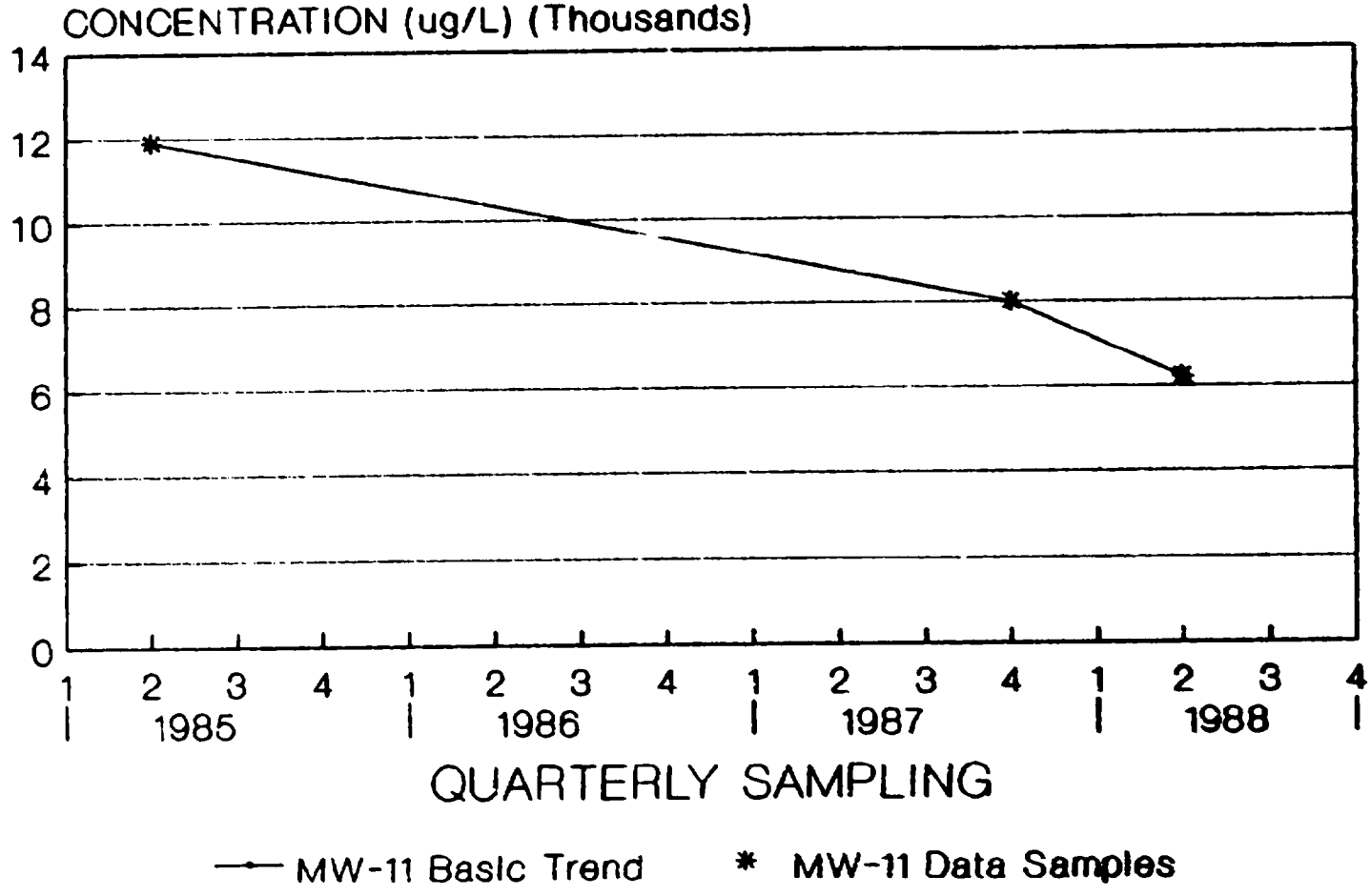

Figure 10. McClellan AFB Well Sampling, Area D

Trichloroethene

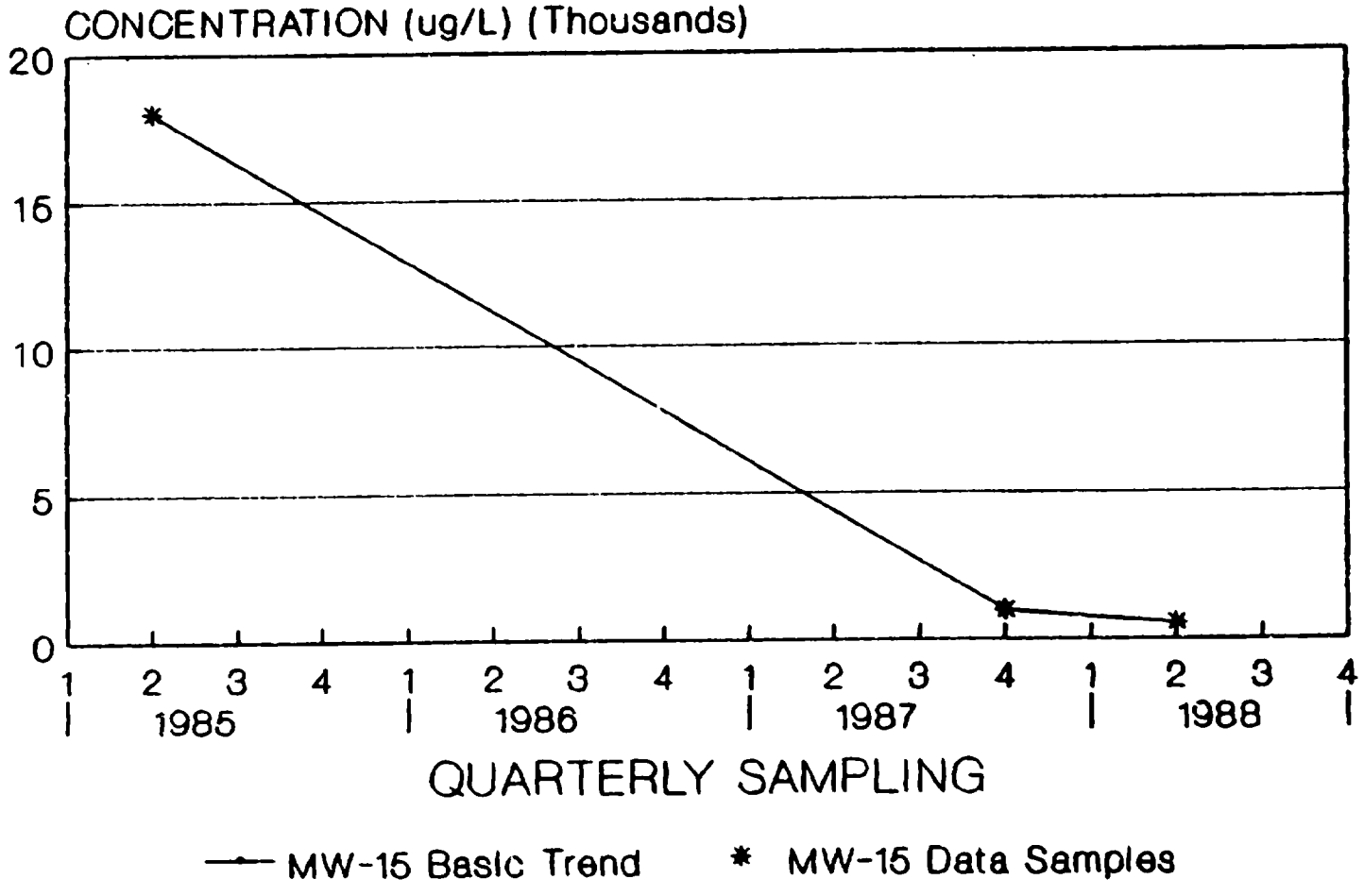

Figure 11. McClellan AFB Well Sampling, Area D

Trichloroethene

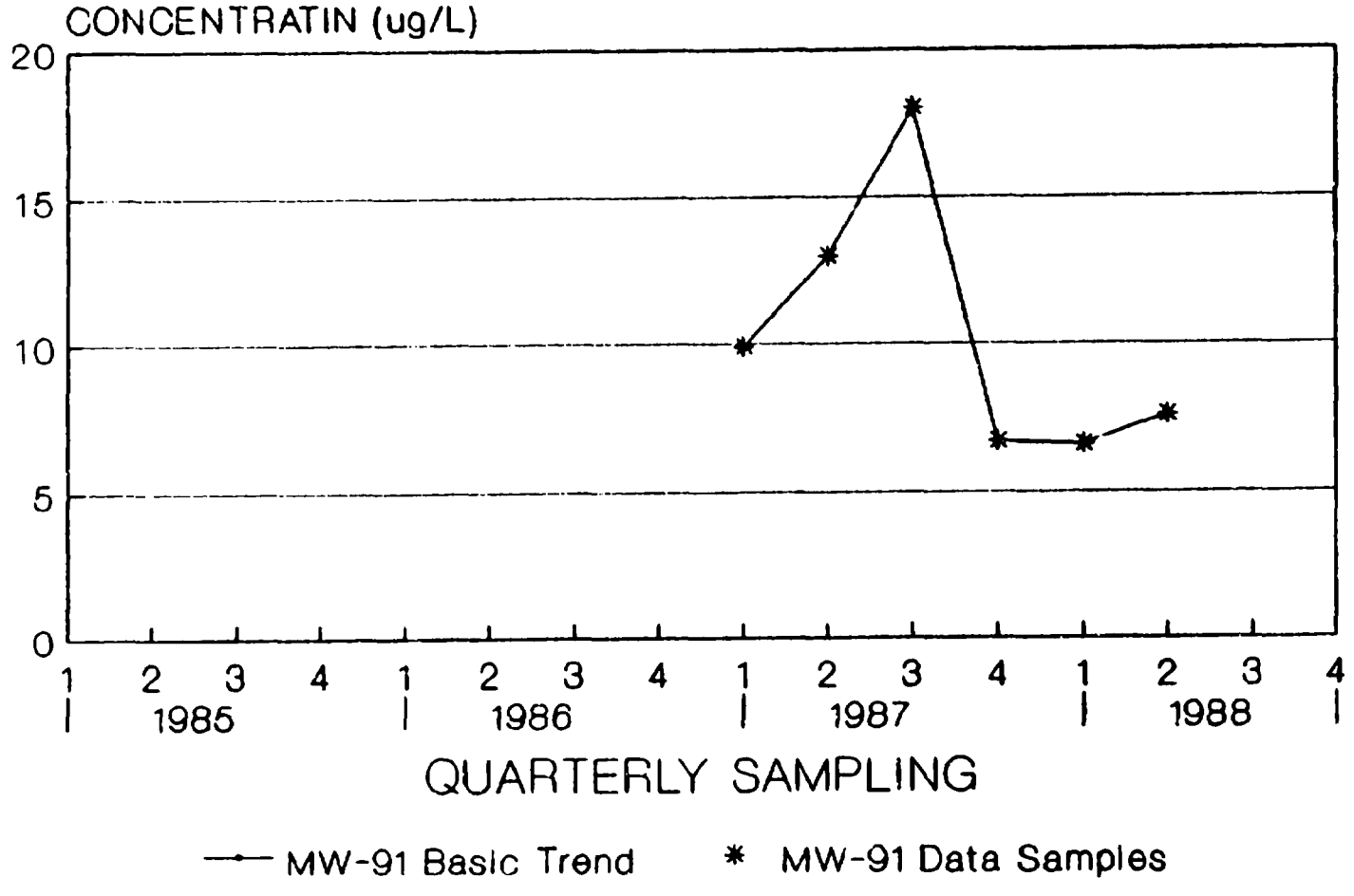

Figure 12. McClellan AFB Well Sampling, Area D

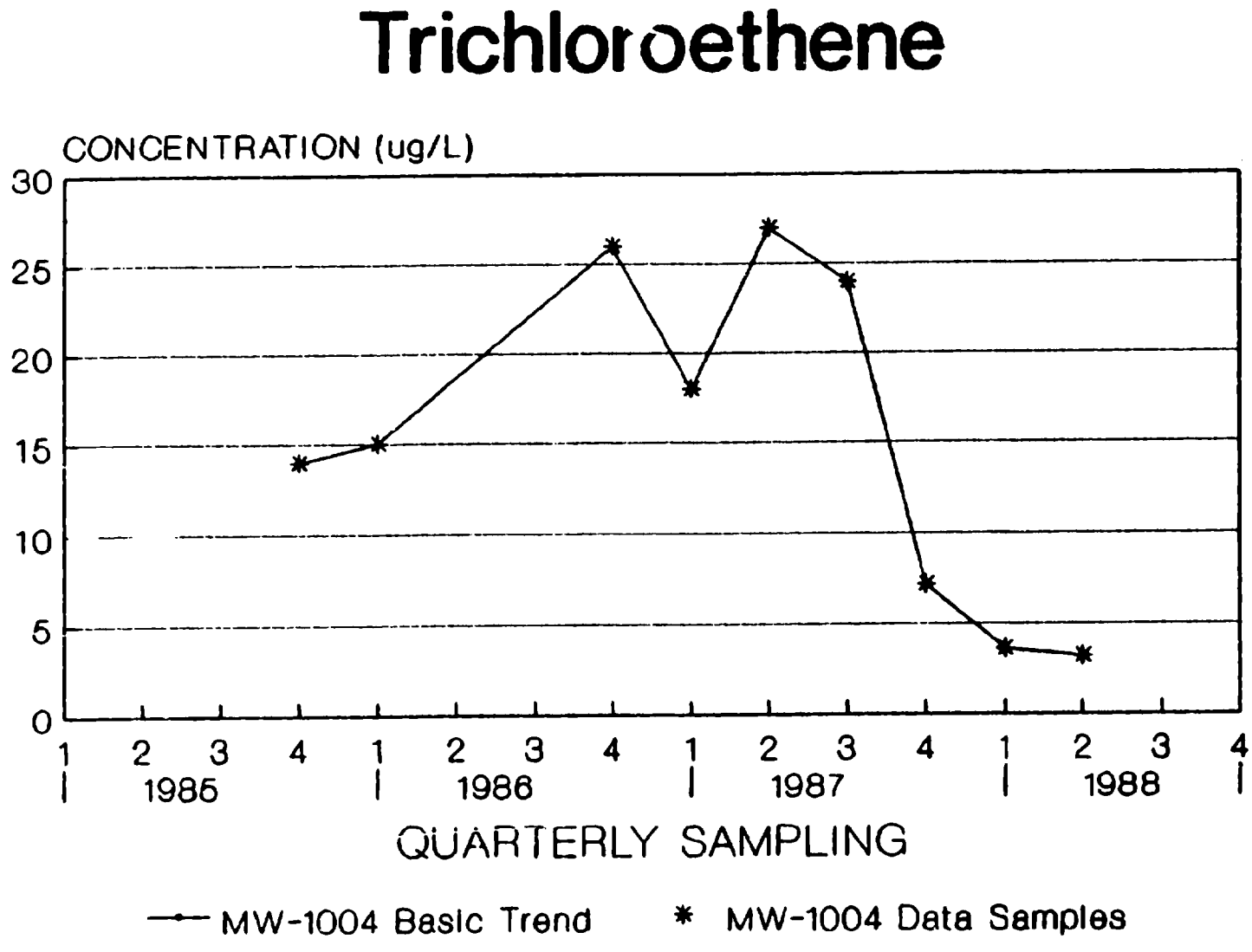

Figure 13. McClellan AFB Well Sampling, Area D

Trichloroethene

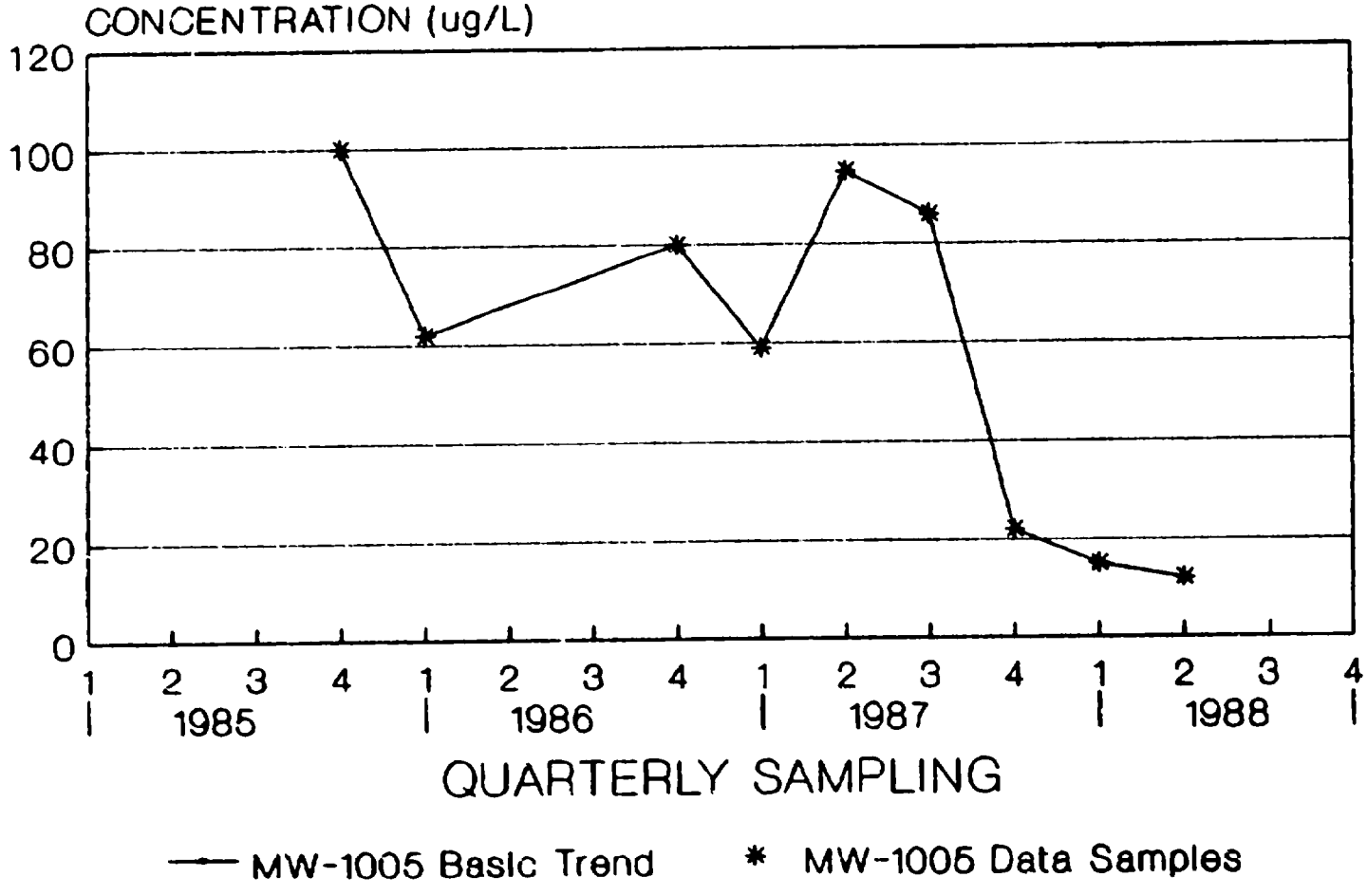

Figure 14. McClellan AFB Well Sampling, Area D

method for remediation has been effective in reducing significantly the levels of contamination in the monitoring wells. However, concentrations still remain above allowable EPA standards. Furthermore, good progress has been achieved in identifying the groundwater gradient flow and reasonable confidence exists that the contaminants are being contained within base boundaries. The greatest problem appears in the monitoring plan used to collect data. The present method does not present a clear picture of the effect pumping has on the movement of the contaminant plume. While most wells show decreases in contamination levels, some wells located near the extraction wells, show increasing levels.

Wright-Patterson AFB

Historically, most of the wastes containing hazardous substances on Wright-Patterson Air Force Base have been generated by industrial aircraft maintenance or overhaul missions; waste oil and solvents from cleaning and painting operations; and fuel spills and leaking fuel tanks near the fire training areas (46:1-25). Areas shown in Figure 15 were found to be among those having the highest contamination potential and include the fire training areas, land fills and past fuel (POL) spills. In 1972, a 1000 to 2000 gallon spill was discovered at spill site 1, and despite records showing the spill was intercepted no data concerning the recovery actions were documented (46:1-15). Except for summary reports concerning past spills, quantitative data records

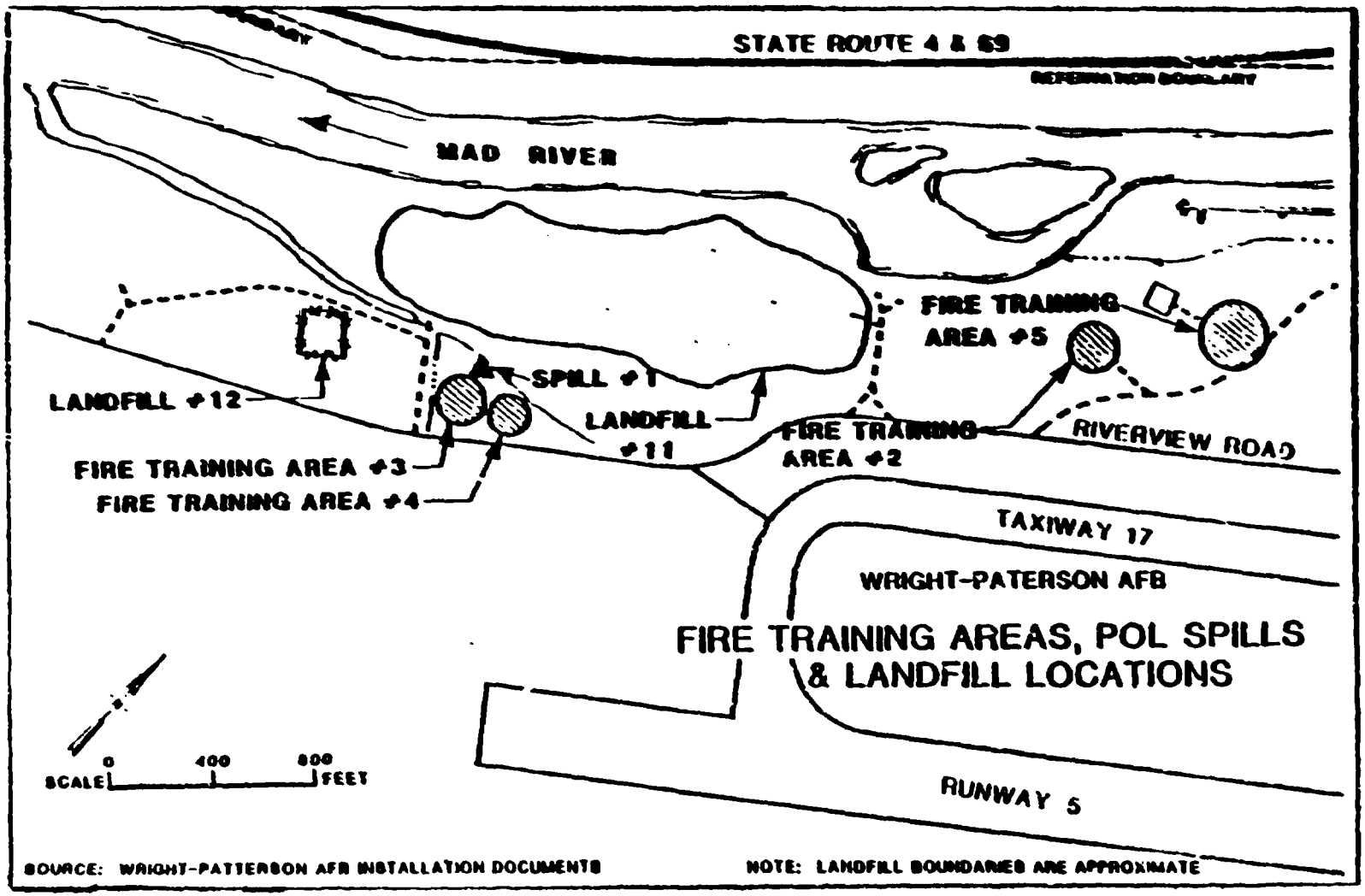

Figure 15. General Site Map of Wright-Patterson AFB

have not been maintained for evaluation purposes. Conversations with several base environmental personnel indicate that major groundwater cleanup efforts for Wright-Patterson Air Force Base are still several years away, pending completion of the final phase IVA feasibility study.

In 1987, however, the air base experienced a 3000 gallon fuel (JP-4) spill at Fire Training Area 5 and contracted the DETOX company to conduct cleanup operations. After several months of pumping, DETOX estimated that only 300 gallons of the fuel had been recovered. Wright-Patterson Air Force Base, unsatisfied with progress, contracted DuPont Biosystems Incorporated to determine the feasibility of using biological treatment on the remaining fuel. Lab tests indicated that the site contained a microbial population that could rapidly degrade the JP-4 fuel when supplied with oxygen and inorganic nutrients. In January 1988, Biosystems initiated a program of adding inorganic nutrients to the site, and recovery of fuel using free product recovery pumps and bailing. Data concerning Biosystems efforts are available in monthly progress reports and are presented in the following discussion to determine the success of their efforts thus far. Since Biosystems is conducting both biodegradation and pumping to remediate the spill, each process will be examined separately.

Based on soil core samples taken prior to the beginning of the treatment phase, Biosystems estimates that there is

between 1665 to 1860 gallons of JP-4 fuel remaining in the area of the fire training site. The actual hydrocarbon concentrations in soil cores taken prior to treatment are provided in Appendix C. According to Biosystems proposed plan, core samples are to be taken every three months. To date, follow-up core samples have not been taken so effectiveness of the process can not be determined directly. The second core sampling is expected sometime in August 1988 and at that time progress may be determined.

Fortunately, the amount of free fuel recovered since the start of pumping has been tracked. As of 30 June 1988, free product pumping and bailing has resulted in recovering 185 gallons of fuel. Figure 16 provides a graphic presentation of current recovery efforts and shows a simple linear forecast for various points in the future using present data. The forecast is based on a 95% confidence factor, but can not be relied on absolutely because of the small sample data field. The amount of free product recovered greatly increased during the months of May and June, and according to Biosystems is attributed to the overall drop in the groundwater elevation during these months. Groundwater levels are giving in Appendix D along with the recorded thickness of fuel in each well. The water elevations were down from 0.72 to 0.80 feet in the three recovery wells during the months of May and June. Making the assumption that this represents a seasonal occurrence, it is predicted using simple linear

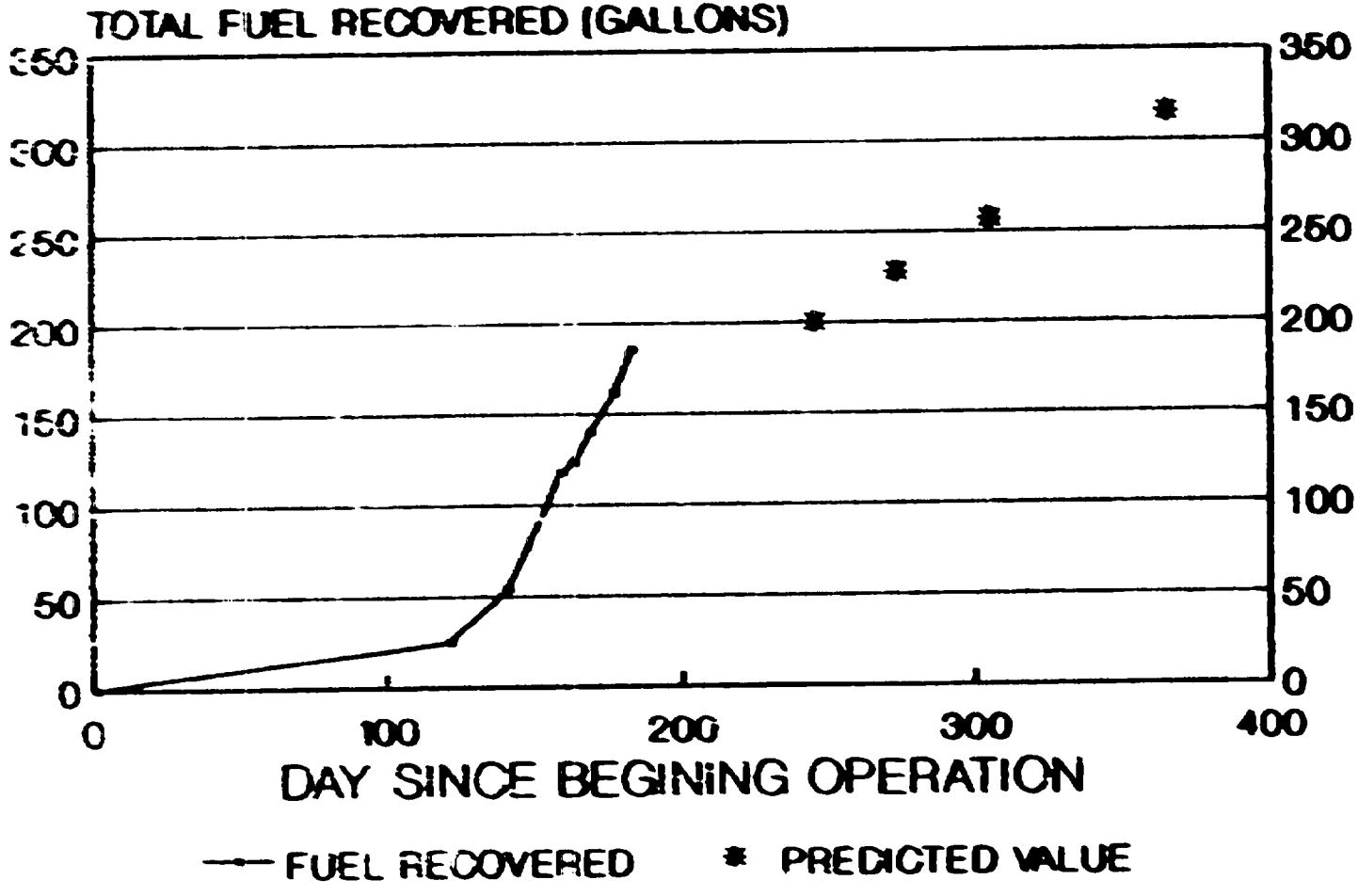

Figure 16. Total Free Fuel Recovered

regression (95% confidence factor) that by the end of the estimated two year program only 659 gallons of free fuel will be recovered by pumping and bailing.

Water samples taken from wells were also analyzed for traces of benzene, toluene, and xylenes. Table III shows the concentrations of selected wells at various times since beginning remediation. In most cases, there is a steady decrease in concentrations to levels at or below 0.005 parts per million (ppm). This reduction suggests that pumping along with biodegradation may have had some effect in lowering contaminant concentrations. The effects of pumping can be detected in the free fuel thickness found in the monitoring wells. Figures 17 through 19 show the reduction due to pumping over time. Under constant pumping the free fuel thickness is greatly reduced, but when pumping is interrupted, as it was in April, the concentrations increase rapidly. This suggests that pulse pumping might be a more effective technique and at the same time reduce the annual operating costs of pumping.

Since only one-third of the fuel is estimated, by this author, to be recoverable through pumping, the remainder must be biodegraded by the addition of nutrients to the fuel spill. The soils at the Wright-Patterson Air Force Base Fire Training Area 5 contain a microbial population that could rapidly degrade the JP-4 (fuel) when supplied with oxygen and inorganic nutrients (4:14). Initial treatment utilized

Table III

Wright-Patterson AFB
Selected Contaminant Concentrations

Well Number	Date	Benzene (PPM)	Toluene (PPM)	Xylene (PPM)
Ø5	Ø3/Ø8/88	<Ø.ØØ5	Ø.314	Ø.854
Ø7	Ø2/18/88	Ø.Ø7	<Ø.ØØ5	Ø.Ø8Ø
	Ø3/Ø8/88	Ø.Ø32	<Ø.ØØ5	<Ø.ØØ5
	Ø3/23/88	<Ø.ØØ5	<Ø.ØØ5	<Ø.ØØ5
	Ø4/25/88	Ø.Ø13	<Ø.ØØ5	<Ø.ØØ5
	Ø5/26/88	Ø.ØØ73	<Ø.ØØ5	Ø.Ø38
	Ø6/22/88	<Ø.ØØ5	<Ø.ØØ5	<Ø.ØØ5
RWA	Ø2/18/88	Ø.Ø3	Ø.Ø1	Ø.Ø2Ø
	Ø3/Ø8/88	Ø.Ø29	<Ø.ØØ5	Ø.Ø12
	Ø3/23/88	Ø.Ø21	<Ø.ØØ5	Ø.Ø1Ø
	Ø3/25/88	<Ø.ØØ5	<Ø.ØØ5	<Ø.ØØ5
	Ø5/26/88	Ø.Ø1Ø	<Ø.ØØ5	<Ø.ØØ5
	Ø6/22/88	Ø.ØØ61	<Ø.ØØ5	<Ø.ØØ5
RWB	Ø2/18/88	Ø.1Ø	Ø.Ø4	Ø.Ø2Ø
	Ø3/Ø8/88	Ø.Ø62	Ø.Ø22	Ø.Ø75
	Ø3/23/88	Ø.Ø33	<Ø.ØØ5	Ø.Ø22
	Ø3/25/88	Ø.Ø37	<Ø.ØØ5	Ø.Ø31
	Ø5/26/88	Ø.Ø213	<Ø.ØØ5	Ø.ØØ8
	Ø6/22/88	Ø.Ø111	<Ø.ØØ5	Ø.Ø56
RWC	Ø2/18/88	Ø.14	Ø.Ø4	Ø.19Ø
	Ø3/Ø8/88	Ø.116	<Ø.ØØ5	Ø.Ø92
	Ø3/23/88	Ø.Ø7Ø	<Ø.ØØ5	Ø.Ø43
	Ø3/25/88	<Ø.ØØ5	<Ø.ØØ5	Ø.ØØ9
	Ø5/26/88	<Ø.ØØ5	<Ø.ØØ5	<Ø.ØØ5
	Ø6/22/88	<Ø.ØØ5	<Ø.ØØ5	<Ø.ØØ5

Data collected from Biosystems Inc
monthly sampling logs

compressed oxygen which supplied approximately 40 mg/L of oxygen at a relatively inexpensive cost (4:15). However, early results showed that only low levels of oxygen were penetrating the contaminated area. Tests are currently being

FIRE TRAINING AREA 5

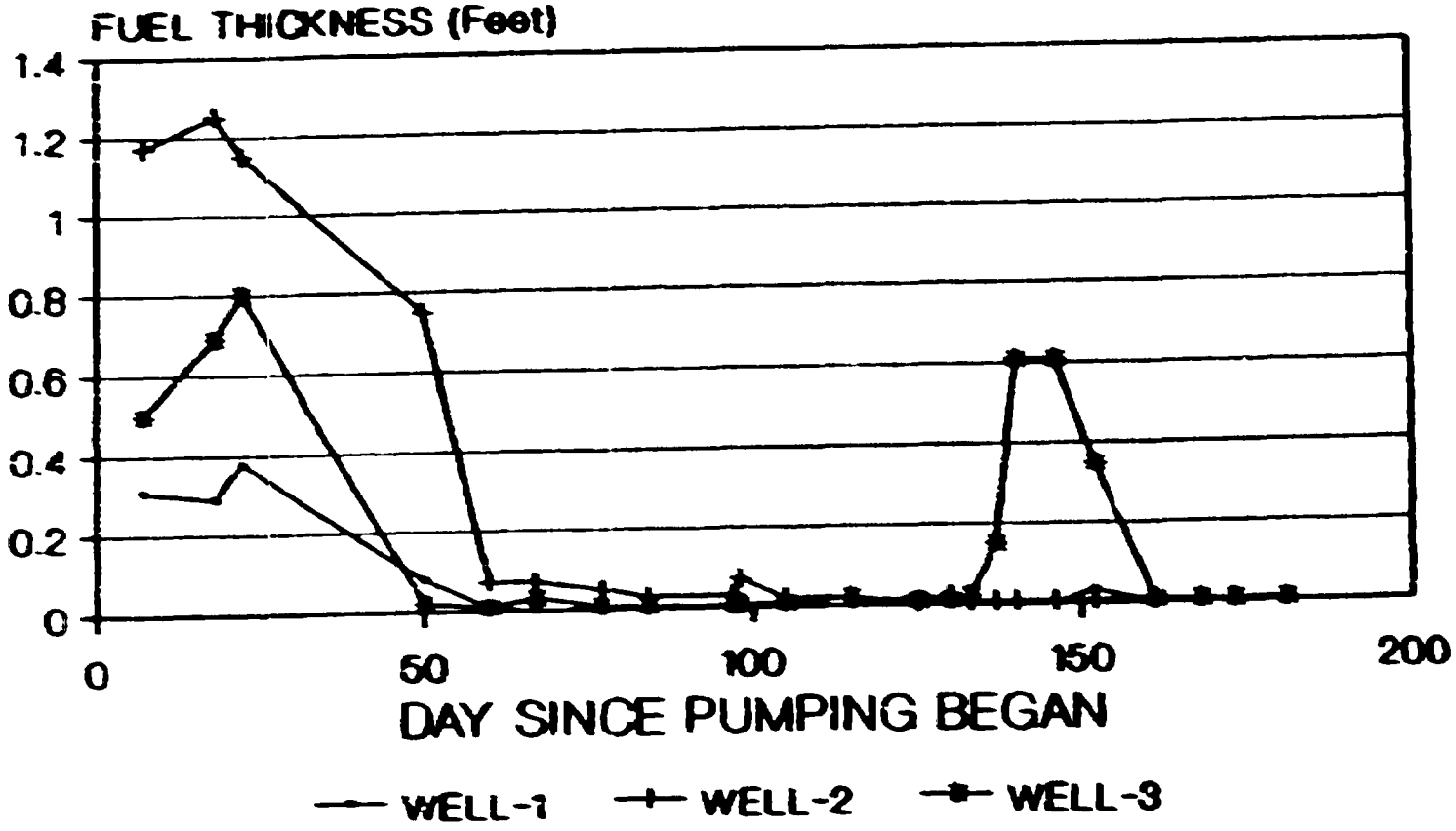

Figure 17. Free Fuel Thickness in Wells 1-3

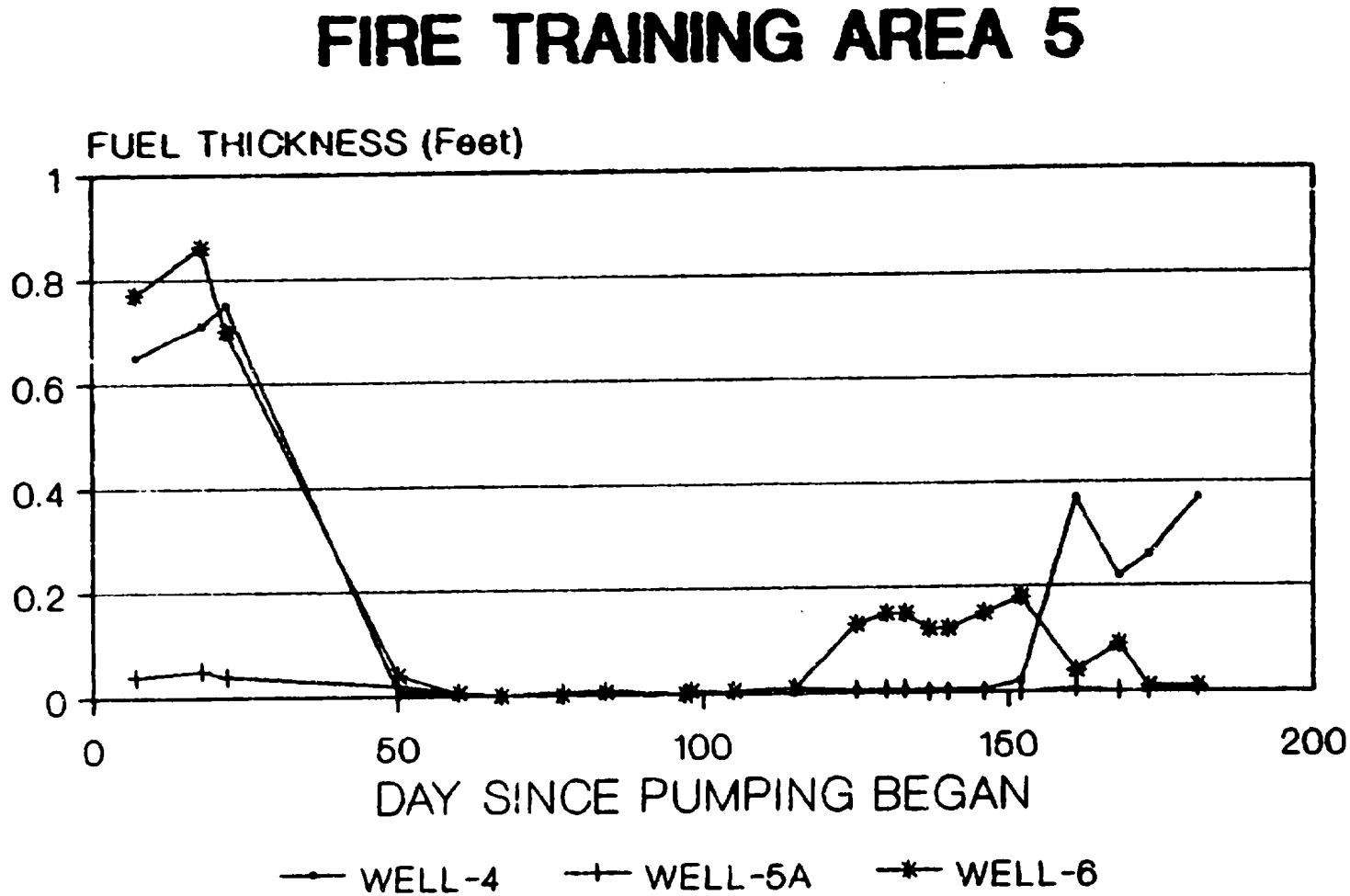

Figure 18. Free Fuel Thickness in Wells 4-6

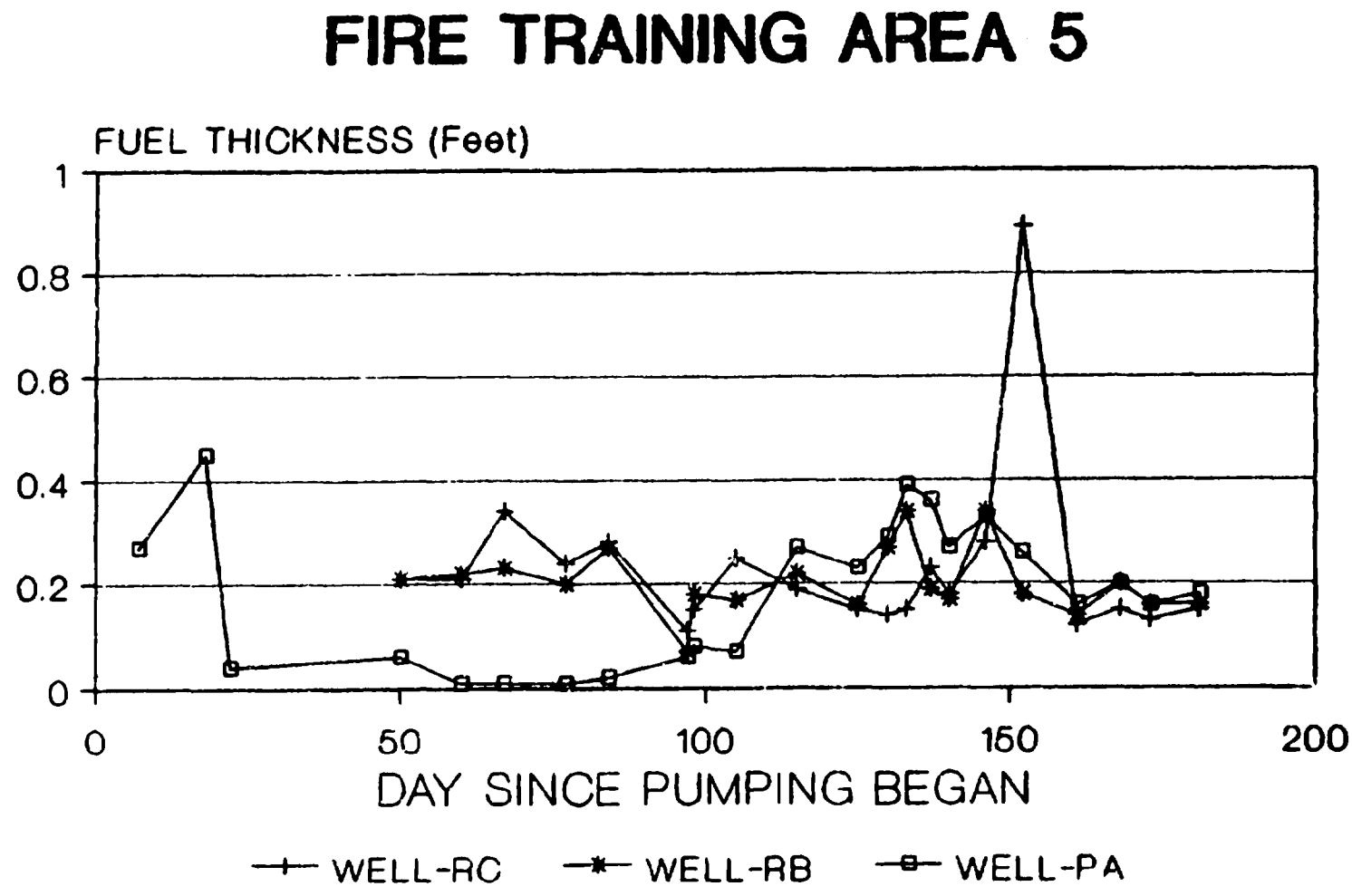

Figure 19. Free Fuel Thickness in Wells RA-RC

conducted, using hydrogen peroxide, to increase oxygen delivery but some plugging has been observed and tests are still continuing. The effect of biological treatment can not be determined directly due to the lack of follow-up sampling but the effectiveness of delivering oxygen to the contaminated area can be evaluated. Table IV shows data extracted from Biosystems monthly progress report dated June 30, 1988 and indicates the wells where measurable amounts of dissolved oxygen have been detected. In addition, Appendix E shows the levels of nutrient and hydrocarbon utilizers which are being detected at the monitoring and recharge wells. Even though nutrients are reaching all areas of the spill site, the concentration is hard to maintain and plugging has been observed. Furthermore, according to several Biosystems progress reports, the chemical analyses of water samples show that the levels of chloride necessary to maintain proper biodegradation continues to be less than that specified by the EPA. Lastly, the flow rates within each recharge well ranged between twenty to forty gallons per minute, slightly lower than the fifty gallons per minute used for the initial proposal. Although lacking updated core samples, it is doubtful that remediation using biodegradation will be completed within the two-year time estimate. Furthermore, given the results obtained from the Eglin and Kelly field tests, the costs of supplying oxygen to the site may prove higher than expected.

Table IV

Water Analysis of Monitoring Wells
Wright-Patterson AFB

Date	Dissolved Oxygen (PPM)	Ammonia Nitrogen (PPM)	Chloride PPM
Well-1			
05/19/88	<0.4	22.4	55.0
05/26/88	<0.4	26.5	56.0
06/27/88	<0.4	25.0	55.0
Well-2			
05/19/88	<0.4	4.5	85.0
05/26/88	0.4	7.0	66.0
06/27/88	0.4	6.2	50.0
Well-3			
05/19/88	<0.4	1.9	86.0
05/26/88	<0.4	2.9	67.0
06/27/88	<0.4	1.9	65.0
Well-4			
05/19/88	<0.4	1.9	65.0
05/26/88	<0.4	1.9	15.8
Well-5			
05/19/88	<0.4	1.0	.0
05/26/88	<0.4	2.3	53.0
Well-6			
05/19/88	<0.4	4.1	79.0
05/26/88	<0.4	5.0	79.0
Well-7			
05/19/88	<0.4	4	75.0
05/26/88	<0.4	[illegible]	57.0
06/27/88	0.8	6.8	50.0

Wurtsmith AFB

Wurtsmith Air Force Base located in northeastern lower Michigan, has been treating groundwater contaminated by TCE since November 1977. The majority of the TCE contamination resulted from a leak in a buried storage tank located near Building 43 (see Figure 20). "From November 1977 through June 1985, about 900 gallons of trichloroethene were removed from the aquifer" (8:20).

The main trichloroethene purge system went into operation in December 1981 with the addition of purge wells PW1, PW2, PW3, and PW4, each having a pumping capability of 300 gallons per minute (8:14). These wells were added to the existing well system to help control the migration of TCE contamination. Figure 20 shows the location of the various wells and the general spread of contamination as of April 1985.

Estimates made in 1985, of future contaminant concentrations, used both linear and exponential regression to predict concentration levels. In order to reduce concentrations down to 50 ug/L, the linear regression model estimated attainment by September 1986 while the exponential regression model predicted the 50 ug/L level would not be reached until May 1988 (8:20). Since concentrations as of June 1988 remain about 100 ug/L, the regression equations failed to perform as expected. This may be the result of regressing individual well samples

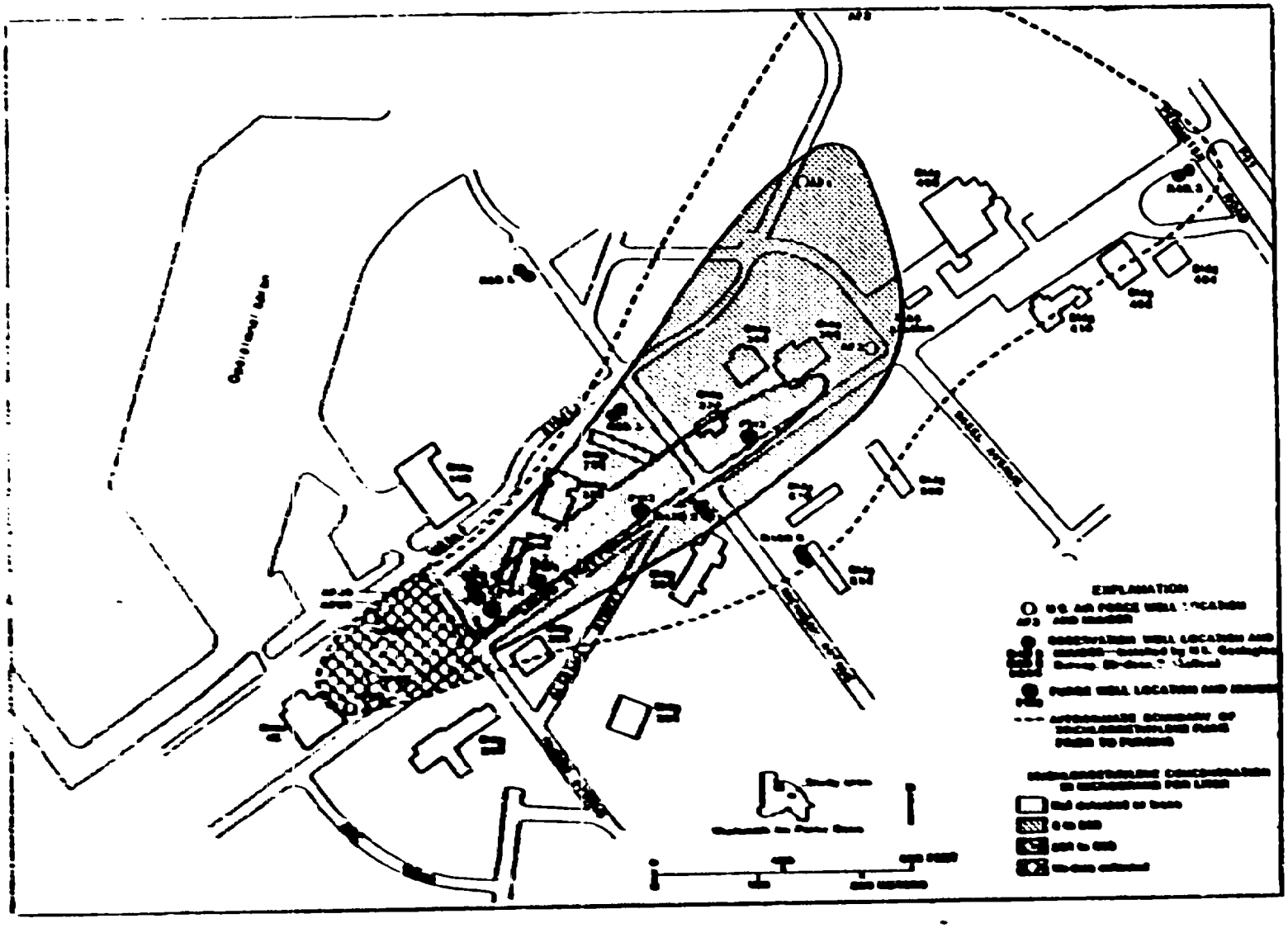

Figure 28. General Base layout and TCE Plume, April 1983

In order to determine the effectiveness of pumping operations, several curves are constructed from the data in Appendix F. First, each well concentration is plotted against time to determine the general trend of concentration reduction within each well. Figures 21 and 22, plotted against a logarithmic scale, show a steady decrease in concentration levels for all wells down to the present level of about 100 ug/L. Visually extending the composite trend of pumping wells P-1, P-3, and P-4 the predicted 50 ug/L level is not reached until mid 1998. Furthermore, extending the trend to the required EPA standard of 5 ug/L, the level would not be reached until sometime in 1997.

"The purging of the Building 43 TCE plume is continuing using an air sparger followed by an activated carbon system" (35:IV-49). The current system operation began in 1981, and is operating at 900 gallons per minute. In 1985, base personnel estimated that this purge system would need to be operated for 20 years before TCE concentrations are reduced to the 1.5 ppb (parts per billion) requested by the Michigan Department of Natural Resources (MiDNR) (35:IV-49). This estimate follows closely the prediction made, by this author, for cleanup to be completed sometime in the late 1990s.

A second series of plots are needed to determine the effectiveness of TCE cleanup by pumping. The curves presented in Figures 21 and 22 indicate that the rate of TCE extraction in most wells is beginning to level off. This

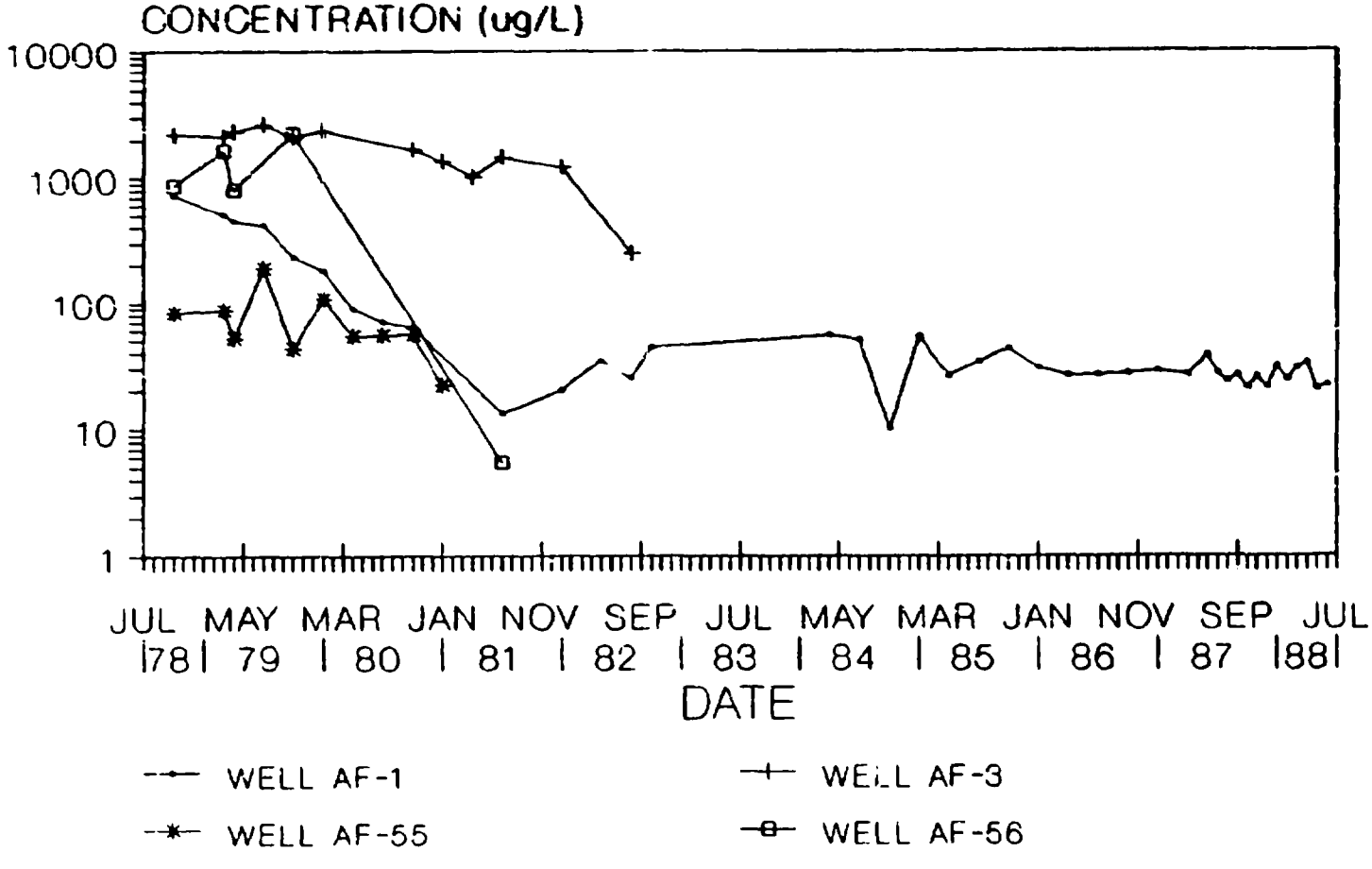

Figure 21. Wurtsmith AFB Monthly TCE Concentrations

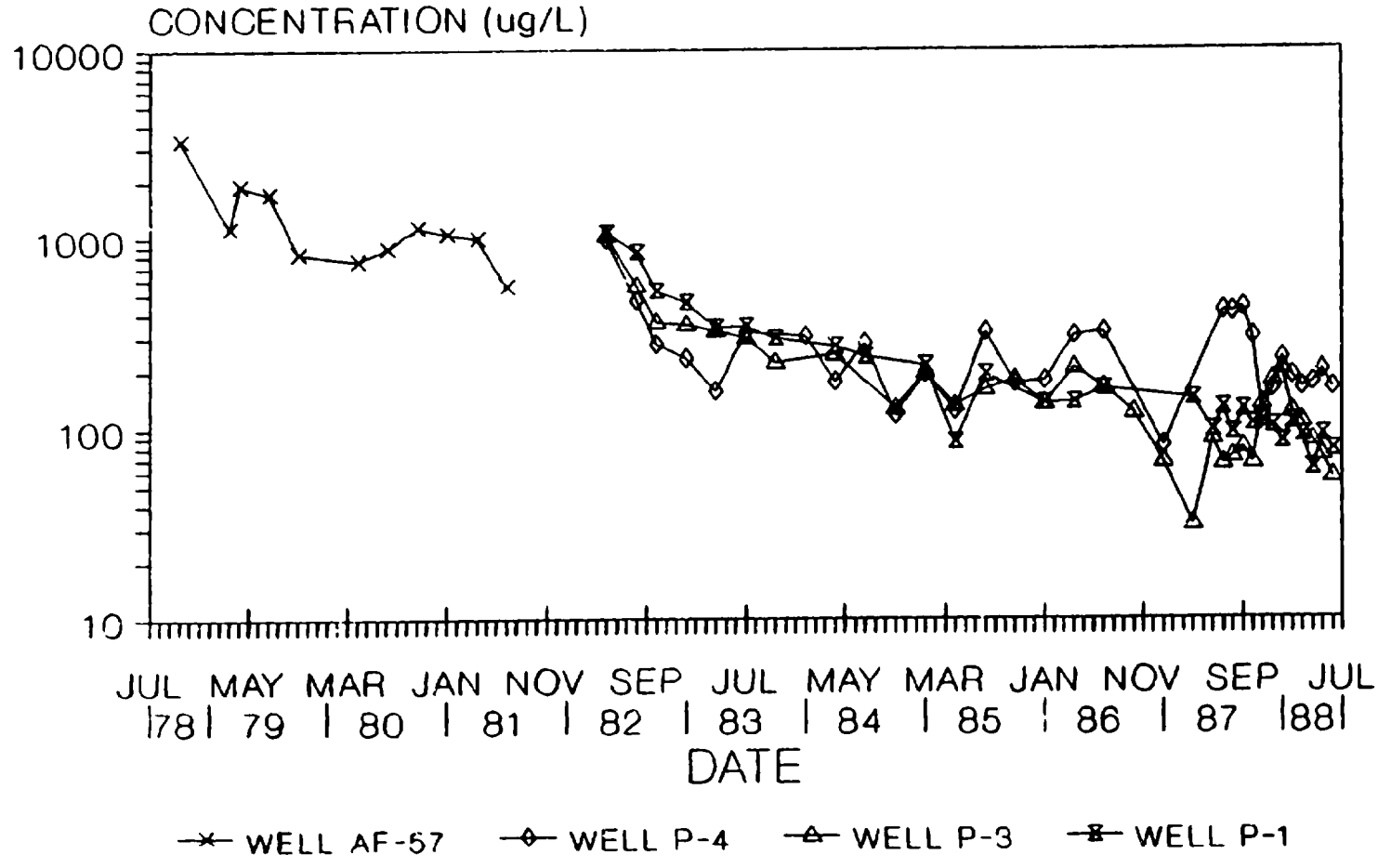

Figure 22. Wurtsmith AFB Monthly TCE Concentrations

might indicate that the TCE levels being detected might be the result of clean water being contaminated by the slow leaching of contaminants from the soil. If this is true, earlier estimates for meeting EPA standards are too short. Figure 23 shows the relationship between the amount of water pumped to the levels of TCE purged. Except for the sudden increase in 1982, when larger pumps were installed, the levels of TCE extracted appear to have stabilized and that an average pumping rate of around 25 million gallons a year is sufficient to maintain TCE extraction rates.

Figure 24, also, shows the relationship of pumped water to purged TCE concentrations, but uses an exponential smoothing method. The curve, therefore, indicates that the amount of TCE which can be extracted for each thousand gallons of water pumped has leveled out. The wide fluctuations in the curve can be accounted for by missing or lost data of some wells and may be ignored.

The stabilization of extraction rates suggests that current forecasts, of when cleanup can be complete, may be optimistic. In order to maintain effective remediation progress, it may be necessary to consider other in-situ methods of remediation. Another alternative would be to use a pumping scheme, such as pulse pumping, to allow the TCE concentrations to increase thus lowering operating costs by increasing extraction efficiency.

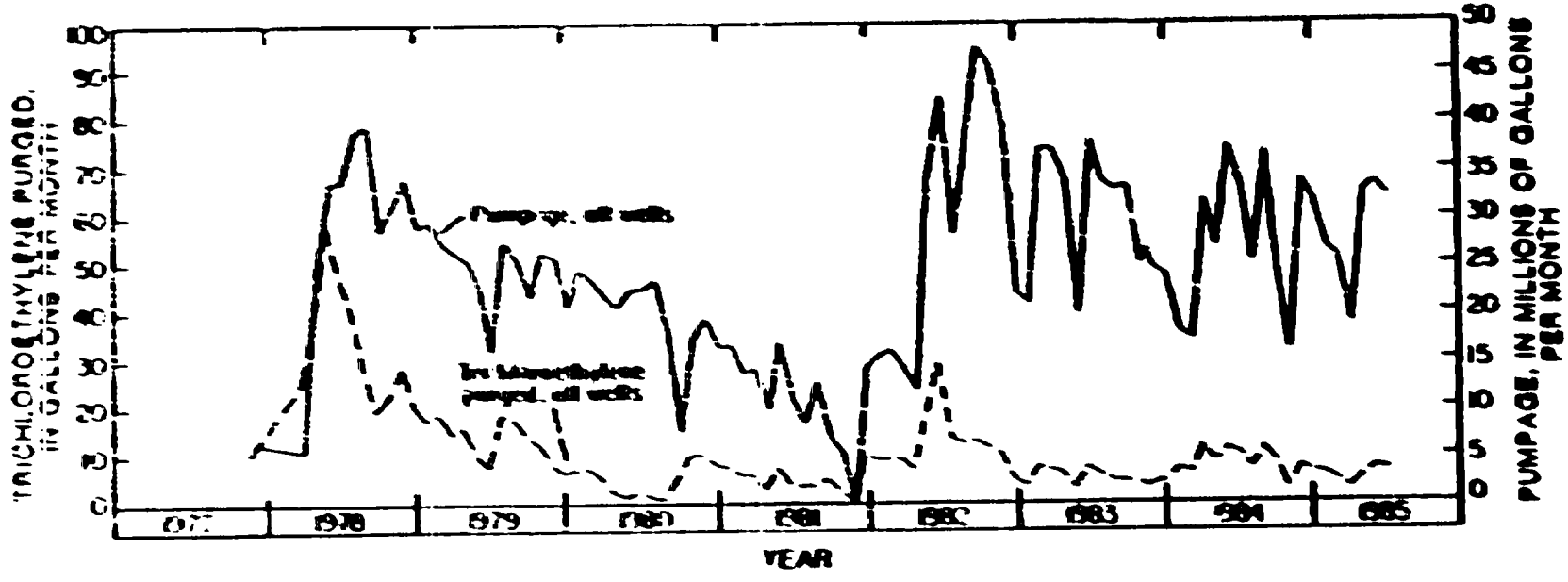

Figure 23. Relation of Purge Pumping to TCE Concentrations

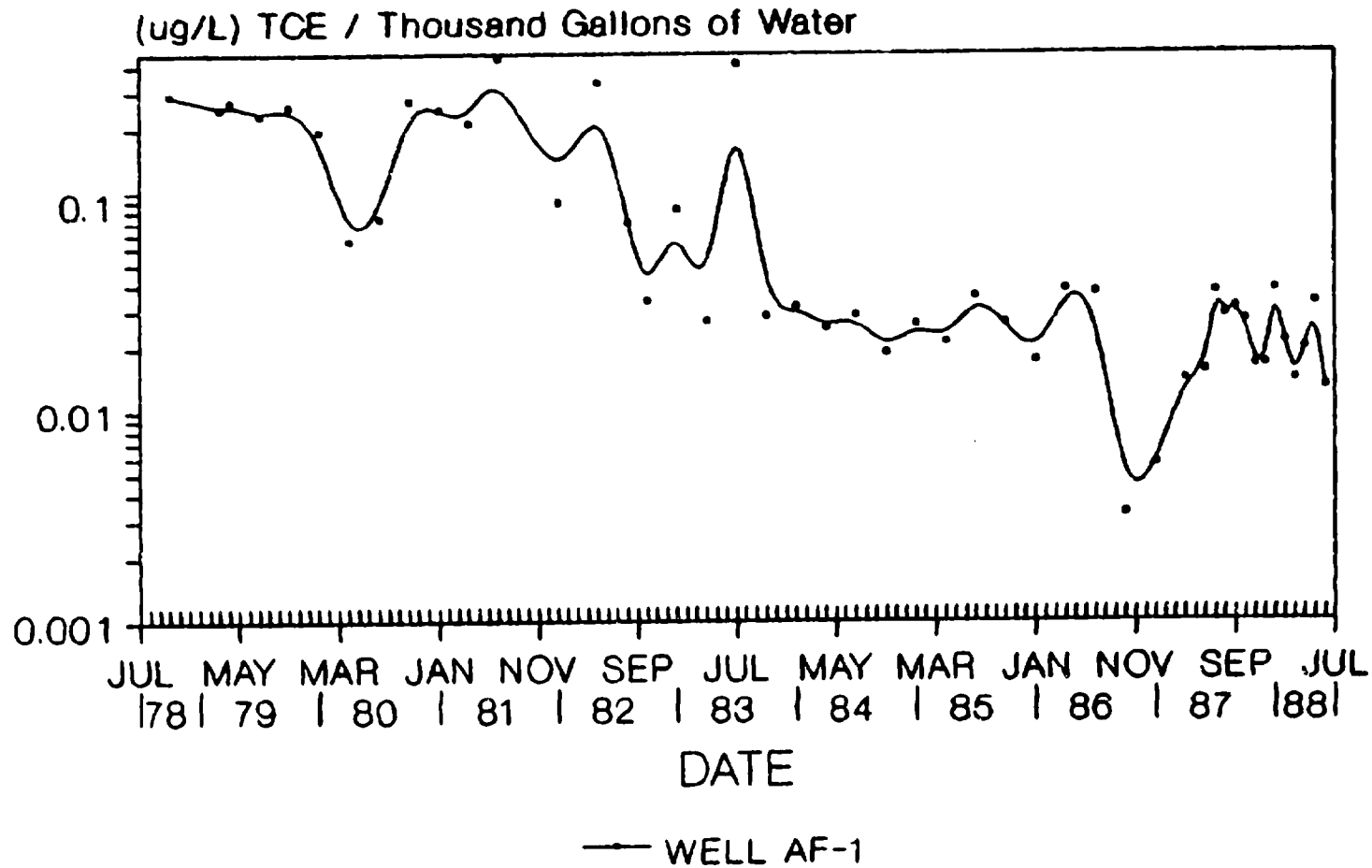

Figure 24. Composite Ratio of TCE to Water Pumped

Summary

This chapter presented the results and analysis of three case studies using various forms of pump-and-treat technology. Two of the studies, McClellan Air Force Base and Wurtsmith Air Force Base, use similar extraction schemes to remove contaminated groundwater but apply different treatment processes. While both show significant lowering of contaminant concentrations each fail to meet standards specified by the EPA. Furthermore, both are predicting earlier cleanup than present data supports. McClellan's sampling plan does not provide a clear picture of the location of total contaminant and the significance of contaminant trends at selected wells.

Wurtsmith Air Force Base has been performing treatment the longest and is still showing readings 100 times above the allowable limits. The most recent data indicates that extraction rates have stablized and that complete compliance with EPA standards is a long time away. Results, furthermore, indicate that for pumping, at this site, to meet regulatory standards alternative methods may need to be applied.

Lastly, the combined pumping and biodegradation effort at Wright-Patterson Air Force Base has not been in operation long enough to draw any valid conclusions. However, it is clear that pumping will not completely remediate the fuel problem. Reports on similar biological treatment efforts at

other test sites, also, spread doubt on the efficiency of that method to achieve required results in a cost effective manner.

V. Conclusions and Recommendations

Introduction

This chapter presents conclusions and recommendations based upon results of the research study. Even though the main objective of determining the effectiveness of the Air Force pump-and-treat method was not accomplished, each of the five investigative questions will be addressed and compared with those case studies for which quantitative data was collected.

Since the quantity of data fell short of what was desired, a comprehensive evaluation of the Air Force application of pump-and-treat technology is precluded. However, information obtained from the case studies provides a good start in identifying the necessary data needed to properly evaluate current groundwater treatment programs.

Following the conclusions, recommendations are presented on how this study can be expanded and ways are suggested in which Air Force groundwater remediation can be better evaluated. This paper makes recommendations based on research findings and indicates additional areas of study needed to provide better management of current technology given our limited resources.

Conclusions

Research Question 1. The pump-and-treat approach to groundwater remediation is currently the Air Force's preferred method of treatment. All of the groundwater treatment programs currently being managed at Air Force installations within the CONUS involve some form of pumping. The particular treatment varies depending on the nature of the contaminant, with activated carbon and air stripping being the most popular and economical methods.

Bases experimenting with other methods typically rely on bioremediation to remove contaminants (specifically hydrocarbons such as fuel), which can not be extracted by pumping. With this method of treatment, injection wells are needed to deliver nutrients and oxygen to the biological organisms.

Research Question 2. The Air Force currently has no specific criteria for determining the effectiveness or success of groundwater treatment programs. According to a telephone interview with Lieutenant Colonel Tom Lubozynski, RDV, Environics Division of the Engineering and Services Laboratory, Air Force Engineering and Service Center, Tyndall AFB, each base is tasked with conducting it's own evaluation based on requirements established by state and federal environmental agencies. Since each site poses specific problems unique to that area, it is viewed that a compre-

hensive policy dictating levels of performance would be impractical and restrict development of new technology.

Research Question 3. Improvement in groundwater contamination levels has occurred at all bases where pumping is being conducted but sampling is restricted to water purged by pumping. Even though the water samples are showing significant decreases in contaminant concentrations compared with those taken prior to treatment, the levels still remain well above limits permitted by the federal Environmental Protection Agency. Furthermore, the levels of contaminant remaining absorbed to the soil are not directly affected by pumping.

Among the few bases indicating significant progress in their treatment programs are McClellan Air Force Base and Wurtsmith Air Force Base. McClellan will be publishing a report in late August 1988, detailing the results of their program along with a self evaluation of effectiveness. Some of the data used in preparing McClellan's report was obtained and analyzed. Overall, the sample well readings indicate great initial reductions in contaminant levels but these results may be misleading given the sampling scheme used.

Wurtsmith AFB, also, has succeeded in major reductions of TCE concentrations through pumping and air stripping. Base personnel are predicting a mean TCE concentration of 50 ug/L for purge wells by 1988. This figure is based on applying exponential regression to frequently recorded data

samples. When the contaminant concentrations reaches 1.5 ppb, TCE treatment can be terminated.

Research Question 4. Duration of groundwater treatment varies with each site and often takes longer than expected. McClellan's treatment plant has been in full operation for about two years and despite impressive initial contaminant reductions, it appears effective remediation will take a long time.

Wurtsmith has been conducting pumping operations for TCE contamination since 1977. Original estimates called for TCE cleanup to be completed by 1983, but instead larger pumps had to be installed. According to Michael Miklow, Environmental Coordinator at the base, Wurtsmith is getting close to the cleanup goal established by the courts for site closure, even though the 1.5 ppb requirement set by the MDNR may not be reached for some time. Analysis of the data and estimates from base personnel indicate that to reach 5ug/L will require about ten more years.

Wright-Patterson AFB, on the other hand, has just begun treatment of a fuel spill in the fire training area and estimates that its program of pumping and biological treatment will take about two years. However, after six months of treatment only 185 gals of fuel has been recovered. Furthermore planned core sampling to determine the effect of biological treatment has not been accomplished. To date, only water samples have been taken to monitor the delivery of

nutrients to the spill. Based on analysis of available data this project should take longer than expected.

Research Question 5. One major problem with the pump-and-treat method is that only contaminants suspended in water can be extracted for treatment. Contaminants that cling to, or interact with, the soil can not be effectively treated by pumping. Furthermore, literature suggests that many spills remain in the unsaturated zone and slowly filter into the groundwater thus extending treatment longer than expected. The current data collected concentrates on contaminant concentrations detected in water samples and measurements of groundwater gradients. Very little attention is given to the total amount of contaminant remaining in the subsurface environment. More extensive monitoring is needed to detect and track the movement of contaminants.

Bioremediation technology is a promising method of in-situ treatment that may be used with pump-and-treat to reach contaminants not affected by pumping. While the Wright-Patterson AFB project is still in early stages of development, several problems have occurred. Plugging of infiltration galleries has slowed the delivery of liquid oxygen to the fuel spill area and has led to experimenting with hydrogen peroxide as a substitute oxygen source. However, hydrogen peroxide is extremely unstable and requires adding excess phosphates to control decomposition and prevent wasteful oxygen release near injection points. With the

current cost of 35% hydrogen peroxide over $4.00 per gallon, this waste can easily double costs (18:4). The Engineering and Services Center strongly recommends that contractors conduct small on-site pilot tests to determine the stability of peroxide, attainable pumping rates, and permeability of the soil before deciding to use biodegradation. Improved pumping schemes and other in-situ methods, such as soil venting, may prove more economical.

General Recommendations

A great deal of research is being conducted to come up with new and better methods of groundwater treatment. However, senior Air Force environmental management also needs to take a closer look at the way current programs are being conducted. The following actions are needed in order to make a proper determination of program effectiveness.

1. The method of data collection and retention must be standardized across all commands and maintained in a central data base information system. Currently, quantitative data is maintained at the base or command level and retrieval can be a long and difficult task, especially, when information is maintained in different formats. Already, data is being lost because samples are not taken, or lost in transit. Also, dissimilar data makes a comprehensive evaluation practically impossible. The ability to analyze comprehensive data will better enable groundwater technologies to be matched with

site characteristics and aid in selecting the best treatment alternatives.

2. A specific office needs to be established at the Air Force Headquarters level, that is responsible for monitoring and evaluating the data supplied by each program. Individual bases can still conduct their own evaluation of effectiveness; however, only by comparing the progress of other similar programs can an accurate determination of effectiveness be made.

3. Senior environmental leadership needs to establish, with the Environmental Protection Agency's concurrence, criteria for determining effective clean up progress of groundwater using available technology.

4. Groundwater pumping should be continued but, in some cases, may need to be augmented with other technologies at some point during the treatment. If problems with biological treatment can be overcome it may be a suitable alternative to effectively remediate contamination. Otherwise, other in-situ approaches (e.g. soil venting or vitrification) may need to be developed. A detailed study of contaminant reduction curves and the application of linear and non linear programming can aid in determining the optimum combinations of techniques to minimize total project cost.

In summary, the results of this research effort indicate that serious problems exist in collecting and maintaining quantitative data necessary to determine the effectiveness of

current groundwater treatment programs. Furthermore, program effectiveness is evaluated by each base with summary reports being provided to higher levels of management. This creates an inconsistent evaluation method. Based on the cases for which data was obtained and available literature, pump-and-treat still appears to be the most effective and inexpensive method of treatment.

Recommendations for Future Research

This paper has initiated the collection of data required to evaluate the effectiveness of current pump-and-treat methods. However, because of difficulties encountered during data retrieval, follow on research is required.

First, a comprehensive data base showing the progressive contamination levels for each cleanup program needs to be completed and integrated with the data contained in the appendices. At the present time, an installation restoration program management information system is being developed at Brooks AFB and Bolling AFB to assist in treatment technology selection. This system could be further developed to include data collection, storage, and statistical analysis.

Second, sampling plans need to be developed that provide a clearer picture of contaminant concentrations at a given site. Increases or decreases in concentrations at a particular monitoring well do not provide quantification of total contaminant still present.

Third, effectiveness needs to be defined in measurable terms that include factors such as the remediation method, local hydrogeological conditions, and local regulatory statutes. Ideally, an effective performance equation can be derived through comparisons of contamination reduction curves, and used by managers to aid in the implementation of their cleanup programs.

Appendix A: Command Environmental Contacts
(As of: 6 Jul 1988)

COMMAND/ADDRESS	NAME	AUTOVON/COMMERCIAL
AAC/DEPV Elmendorf AFB, AK Bldg. 6-900, Rm 139 Fax: 5411	Jim Hostman Terese LeFrancois Jeff Ayres	317-552-4151/5340 907-552-4151/5340
AFDW/DEEV (1100 CES) Bolling AFB, DC Bldg. Hangar 1, Rm 107	Capt Andy Perry	297-5443 202-767-5443 Fax: 3106
AFLC/DEV WPAFB, OH Bldg. 280	John Maiorano Jeff Mundey Terry Lyons Richard Hill	787-5873 787-7053/1478 787-5878/9 Fax: 513-257-3241
AFRES/DEPV Robins AFB, GA Bldg. 210 Fax: 5288	Tom Russell Sheryl Faust-Beck	468-5598 912-926-5598
AFSC/DEV Andrews AFB, MD Bldg. 1535	Col Frank Gallagher Terry Yonkers Carrie Wiesse	858-6341/42/43 301-981-6341/42 Fax: 4770/3469
AFSPACECOM/DEPD Peterson AFB, CO Chidlaw Bldg.	Col Byrne Kevin Carroll	692-5187 303-554-5187 Fax: 5493
ANGSC/DER Andrews AFB, MD Bldg. 3500	Ron Watson Gary Hinkle Dan Waltz	858-6691 301-981-4048 Fax: 5281
AFSC/PLM Andrews AFB, MD Bldg. 1535	Les Keffer	858-5130-2862 301-981-5230 Fax: 7097
ASD/PMDA WPAFB, OH Bldg. 16	Lt Peter Reynolds Chuck Garrity	785-3076/4466 513-255-3076 Fax: 7281
ATC/DEEV Randolph AFB, TX Bldg. 661	Lt Col Joe Saenz Ed Cullins Lt Dave Parker	487-2321/3240 512-652-2321 Fax: 3935

Appendix A (continued)

COMMAND/ADDRESS	NAME	AUTOVON/COMMERCIAL
AU/DEEV (3800 CES) Maxwell AFB, AL Bldg. 78	James Caldwell Harvey Teten	875-5260/5664 205-293-5260 FAX: 2692
MAC/DEEV Scott AFB, IL Bldg. 1600	Wayne Caughman Lt Col Jerry Lang Yogish Sheth Vanda Kloke	576-5764 618-256-5764 Fax: 2910/2455
PACAF/DEPV Hickam AFB, HI Bldg. 1102 Fax: 1576	Dick Gordon	315-449-5576/9553 808-449-5576/9553
SAC/DEV Offutt AFB, NE Bldg. 500	Major Doug Brown Capt Sonny Oh Capt John Woodsley	271-5854/3341 402-294-5854 Fax: 5752
TAC/DEEV Langley AFB, VA Bldg. 681	Gill Burnet Capt Bill Stutz Capt Kerry Hartline Joe Fitzgerald	574-4430/7844 804-764-7844/4430 Fax: 3923
USAFA/DEE Colorado Springs, CO Bldg. 8120	Mark Scott	259-4483/2158 303-472-4483/2153 Fax: None
USAFE/DEPV Ramstein AB, GE APO NY 09012-5041	Jim Baker Dave Strainge Capt Tony Williams	480-6481
AFRCE-ER/ROV 526 Title Bldg;30 Pryor St SW, Atlanta, GA	Tom Simms Bobby Ficquette Dave Glass Jane Penny Mary Jane Lampkins	797-1001(ex.331) 404-331-6776/6771 Fax: 2537
AFRCE-CR/ROV 1114 Commerce St, Rm 207, Dallas, TX	Lt Col Miller Tony Robledo	967-1101(ex.653) 214-653-3338/3344 Fax:2612
AFRCE-WR/ROV 630 Sansome St, San Francisco, CA	Phil Iammi Bob Cameron	859-2110(ex.556) 415-556-0885/0886 Fax: 2612

Appendix A (continued)

COMMAND/ADDRESS	NAME	AUTOVON/COMMERCIAL
AFESC/RDV Tyndall AFB, FL	Maj Tom Lubinzinski Maj Nils Akerlaund Maj Terry Stoddard	523-2097/4628 904-283-2097/4628 Fax: 2612
USAFOEHL Broooks AFB, TX Bldg 140	Col Jim Rock, CV Col R. C. Wooten Maj George New	240-2001/2158 512-536-2001 Fax: 2288
AFAAMRL/TH	Maj Mike Shelley	785-2704/8936
HQ USAF/LEEVO Bldg P-4	Maj Scott Smith Maj Roy Salomon Capt Chuck Howell Capt Gerry Hromowyk	297-0275/8936
HQ USAF/LEEVP Bolling AFB, DC 4156/6245	Lt Col Ken Cornelius Maj Miles Carlson Maj Dennis Sullivan Capt Steve Hoar	297-4156/4616 202-767- Telefax: 3106

Other Points of Contact

COMMAND/ADDRESS AUTOVON/COMMERCIAL	NAME	
ENVIRONMENTAL COORDINATOR McClellan AFB, CA	Col Lawell Jerry Robbin	633-1250
ENVIRONMENTAL COORDINATOR WPAFB, OH	Scot Mallette Clair Mendelsohn (Biological)	257-7152
ENVIRONMENTAL COORDINATOR Wurtsmith AFB, MI	Mike Miklow	623-5180

Appendix B: Selected Base Monitoring Wells: Priority Compounds Exceeding State and Federal Water Standards McClellan AFB CA

WELL No.	SAMPLING (ug/L) 6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
Benzene										
W-10	NS	NS	NS	NS	NS	NS	NS	ND	NS	11
W-11	NS	NS	NS	NS	NS	NS	NS	ND	NS	30
W-54	NS	NS	NS	9.5	ND	1.0	ND	ND	ND	ND
W-112	NE	ND	ND	2.2	ND	ND	ND	ND	ND	ND
W-1021	NS	NS	NS	ND	ND	1.1	ND	ND	ND	ND
Carbon Tetrachloride										
W-27D	ND	NS	NS	NS	NS	27	14	9.6	7.1	9.1
Chromium										
W-12	NS	NS	NS	NS	NS	NS	NS	80	NS	10
W-31S	ND	NS	61	12	NS	NS	NS	NS	NS	ND
W-44S	NS	NS	ND	NS	50	NS	NS	NS	NS	53
W-1018	NE	66	72	ND	NS	NS	NS	10	NS	9
Chloroform										
W-128	NE	NE	NE	48	ND	58	57	ND	ND	300
1,2-Dichlorobenzene										
W-10	69.8	NS	NS	NS	NS	NS	NS	170	NS	200
1,4-Dichlorobenzene										
W-33S	ND	NS	NS	6.2	6.1	15	7.1	ND	7.7	6.0
W-128	NE	NE	NE	ND	ND	5.7	5.5	ND	ND	1.1
1,1-Dichloroethane										
W-10	118	NS	NS	NS	NS	NS	NS	330	NS	230
W-11	3560	NS	NS	NS	NS	NS	NS	ND	NS	520
W-12	ND	NS	NS	NS	NS	NS	NS	ND	NS	29
W-14	ND	NS	NS	NS	NS	NS	NS	ND	NS	49
W-15	1780	NS	NS	NS	NS	NS	NS	15	NS	24

Appendix B (Continued)

WELL NO.	SAMPLING (ug/L) 6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
1,1-Dichloroethane (continued)										
W-54	NS	NS	NS	1400	549	150	20	10	2.9	1.1
W-72	NE	NE	NE	NS	NS	64	150	50	66	82
W-76	ND	NS	NS	NS	NS	NS	NS	NS	NS	20
W-1005	NE	41	15	26	12	27	24	7.5	5.2	4.6
1,1-Dichloroethene										
W-10	1500	NS	NS	NS	NS	NS	NS	1100	NS	910
W-11	64300	NS	NS	NS	NS	NS	NS	46000	NS	17000
W-12	25500	NS	NS	NS	NS	NS	NS	11000	NS	8400
W-14	22600	NS	NS	NS	NS	NS	NS	260	NS	5700
W-15	16500	NS	NS	NS	NS	NS	NS	1500	NS	83
W-14	22600	NS	NS	NS	NS	NS	NS	260	NS	5700
W-15	16500	NS	NS	NS	NS	NS	NS	1500	NS	83
W-22D	297	NS	NS	ND	ND	ND	ND	ND	ND	ND
W-33S	ND	NS	NS	2.7	88	ND	3.1	ND	ND	1.7
W-44S	NS	NS	ND	ND	ND	ND	8.5	3.3	3.3	2.8
W-53	ND	ND	ND	ND	ND	ND	2.1	13	11	2.5
W-54	NS	NS	NS	430	171	52	11	22	8.5	0.4
W-55	NS	NS	NS	210	160	310	130	24	33	13
W-57	NS	NS	NS	NS	13	50	1.6	1.2	3.6	.3
W-59	NS	NS	11	270	99	ND	19	15	3.1	.7
W-72	NE	NE	NE	NS	NS	550	1900	520	930	800
W-74	NE	NS	NS	NS	NS	NS	NS	NS	NS	14
W-76	NE	NS	NS	NS	NS	NS	NS	NS	NS	200
W-91	NE	NE	NE	NE	14	14	8.1	3	1.3	.65
W-130	NE	NE	NE	ND	4	6.1	8.6	2.5	2.9	2.7
W-137	NE	NE	NE	NE	NE	NE	NE	NE	ND	6.5
W-104	NE	120	59	100	62	160	150	41	25	16
W-1005	NE	160	99	110	102	160	280	79	58	38
1,2-Dichloroethane										
W-10	94.7	NS	NS	NS	NS	NS	NS	330	NS	390
W-11	NS	NS	NS	NS	NS	NS	NS	ND	NS	86
W-14	2790	NS	NS	NS	NS	NS	NS	ND	NS	36
W-15	NS	NS	NS	NS	NS	NS	NS	NS	NS	6.8
W-33S	ND	NS	NS	62	88	ND	140	ND	ND	450
W-54	NS	NS	NS	39	14	ND	0.2	1.2	0.2	ND
MW-55	NS	NS	NS	2.9	2.9	ND	ND	0.9	1.1	0.3
MW-72	NE	NE	NS	NS	NS	28	140	120	142	100
MW-76	NE	NS	NS	NS	NS	NS	NS	NS	NS	1.4
MW-128	NE	NE	NE	41	ND	63	75	ND	ND	9.6

Appendix B (Continued)

WELL NO.	SAMPLING (ug/L) 6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
1,2-Dichloroethane (continued)										
MW-139	NE	NE	NE	NE	NE	NE	NE	NE	1.8	ND
W-1004	NE	ND	0.7	1.9	ND	ND	ND	0.9	0.4	0.3
W-1005	NE	5	9.8	14	5.7	7.9	ND	5.1	2.2	1.4
Total-1,2-Dichloroethene										
W-10	ND	NS	NS	NS	NS	NS	NS	780	NS	51
W-14	NS	NS	NS	NS	NS	NS	NS	ND	NS	27
W-27D	NS	NS	NS	NS	NS	18	30	26	23	28
W-33S	ND	NS	NS	ND	530	340	690	430	490	460
W-41S	ND	NS	ND	ND	ND	24	20	17	20	22
W-55	NS	NS	NS	ND	27	11	7.5	5.7	12	6.5
W-63	NS	NS	ND	ND	ND	65	68	52	43	33
W-72	NS	NS	NS	NS	NS	48	75	74	99	57
W-76	NE	NS	NS	NS	NS	NS	NS	NS	NS	29
W-120	NE	NE	ND	ND	ND	23	ND	18	10	17
W-131	NE	NE	NE	6.8	6.1	11	34	27	14	24
W-128	NE	NE	NE	19	230	250	400	ND	420	530
W-132	NS	NS	NS	19	17	32	28	29	33	22
W-139	NE	NE	NE	NE	NE	NE	NE	NE	24	16
W-140	NE	NE	NE	NE	NE	NE	NE	NE	21	14
W-141	NE	NE	NE	NE	NE	NE	NE	NE	41	6.0
W-1005	NE	43	ND	ND	9.4	29	16	14	5.1	2.5
1,2-Dichloropropane										
W-33S	ND	NS	NS	ND	19	23	13	ND	ND	19
W-128	NE	NE	NE	14	ND	19	16	ND	ND	7.7
Lead										
W-12	NS	NS	NS	NS	NS	NS	NS	60	NS	ND
W-1001	NE	NS	60	ND	NS	NS	NS	NS	NS	NS
W-1012	NE	240	ND	ND	NS	NS	ND	NS	NS	NS
Methylene Chloride										
W-10	55.3	NS	NS	NS	NS	NS	NS	NS	NS	0.6
W-11	3140	NS	NS	NS	NS	NS	NS	1700	NS	260
W-14	11400	NS	NS	NS	NS	NS	NS	ND	NS	13
W-15	1790	NS	NS	NS	NS	NS	NS	ND	NS	0.7
W-29D	ND	NS	270	ND	ND	ND	ND	ND	ND	ND
W-36S	ND	NS	12	860	ND	ND	2.2	ND	ND	ND

Appendix B (Continued)

WELL NO.	6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
SAMPLING (ug/L)										
Methylene Chloride (continued)										
W-55	NS	NS	NS	320	ND	ND	ND	ND	ND	ND
W-59	NS	NS	ND	520	ND	ND	ND	ND	ND	ND
W-103	NE	390	ND	ND	ND	ND	ND	ND	ND	ND
W-104	NE	ND	870	ND	ND	ND	ND	ND	ND	ND
W-105	NE	220	420	ND	ND	ND	ND	ND	ND	ND
W-112	NE	260	12	ND	ND	ND	1.4	ND	ND	ND
W-115	NE	680	ND	ND	ND	ND	ND	ND	ND	ND
W-1001	NE	310	18	ND	ND	ND	ND	ND	ND	ND
W-1005	NE	ND	ND	72	4.4	0.4	ND	ND	ND	ND
W-1013	NE	ND	ND	230	ND	ND	ND	ND	ND	ND
W-1019	NE	13	3.0	510	ND	ND	ND	ND	ND	ND
Tetrachloroehtene										
W-10	64.9	NS	NS	NS	NS	NS	NS	ND	NS	2.4
W-11	2480	NS	NS	NS	NS	NS	NS	ND	NS	25
W-12	1260	NS	NS	NS	NS	NS	NS	ND	NS	200
W-14	ND	NS	NS	NS	NS	NS	NS	ND	NS	7.6
W-33S	ND	NS	NS	ND	9.8	8.7	6.9	ND	ND	26
W-41S	3.3	NS	0.6	0.2	ND	0.8	ND	3.2	6.2	10
W-54	NS	NS	NS	4.1	ND	ND	ND	ND	ND	ND
W-55	NS	NS	NS	13	46	47	ND	25	6.8	3.0
W-128	NE	NE	NE	ND	ND	23	ND	ND	ND	10
W-1021	NE	NE	NE	2.8	ND	5.6	2.7	3.3	1.3	1.3
Toluene										
W-54	NS	NS	NS	230	4.7	2.7	ND	.4	.8	ND
1,1,1-Trichloroethene										
W-10	327	NS	NS	NS	NS	NS	NS	ND	NS	36
W-11	18100	NS	NS	NS	NS	NS	NS	10M	NS	3800
W-12	12400	NS	NS	NS	NS	NS	NS	3200	NS	1200
W-14	22800	NS	NS	NS	NS	NS	NS	350	NS	3100
W-15	4100	NS	NS	NS	NS	NS	NS	180	NS	110
W-33S	ND	ND	ND	ND	0.3	0.5	280	ND	ND	1.4
Trichloroethene										
W-10	826	NS	NS	NS	NS	NS	NS	910	NS	1500
W-11	11900	NS	NS	NS	NS	NS	NS	8000	NS	6200

Appendix B (Continued)

WELL NO.	6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
				SAMPLING		(ug/L)				
Trichloroethene (continued)										
W-12	12100	NS	NS	NS	NS	NS	NS	4700	NS	2500
W-14	26600	NS	NS	NS	NS	NS	NS	350	NS	6500
W-15	18000	NS	NS	NS	NS	NS	NS	1000	NS	550
W-19S	4.3	NS	2.6	8.2	NS	NS	NS	NS	NS	NS
W-22D	213	NS	NS	ND	ND	ND	ND	ND	ND	ND
W-27D	4.6	NS	NS	NS	NS	195	76	40	55	56
W-28D	8.9	NS	NS	NS	NS	ND	ND	ND	ND	ND
W-33S	22600	NS	NS	25M	27M	25M	52M	35M	23M	26M
W-36S	2.9	NS	1.8	2.2	ND	3.7	5.3	1.8	1.9	2.6
W-41S	23.2	NS	20	44	37	91	130	100	220	220
W-54	NS	NS	NS	9	3.9	ND	ND	1.8	1.4	ND
W-55	NS	NS	NS	110	70	51	37	7.0	11	4.6
W-57	NS	NS	NS	2.5	14	ND	ND	0.6	2.3	ND
W-59	NS	NS	12	290	108	ND	13	6.2	2.3	0.9
W-61	NE	NE	3.1	7.4	22	23	14	5.3	5.4	5.2
W-63	NE	NS	40	24	41	210	190	52	69	44
W-72	NE	NE	NE	NS	NS	410	1200	560	870	1900
W-74	NE	NS	NS	NS	NS	NS	NS	NS	NS	11
W-75	NE	NS	NS	NS	NS	NS	NS	NS	NS	21
W-76	NE	NS	NS	NS	NS	NS	NS	NS	NS	5.2
W-91	NS	NS	NS	NS	9.9	13	18	6.7	6.6	7.6
W-92	NS	NS	NS	NS	6.2	7.9	9.4	3.8	4.4	4.1
W-120	NE	NE	24	20	19	25	26	9.3	10	12
W-128	NE	NE	NE	41M	28200	55M	68M	27M	30M	27M
W-129	NE	NE	NE	130	10	48	610	45	23	27
W-131	NE	NE	NE	29	19	30	120	55	32	52
W-132	NE	NE	NE	90	62	110	110	110	77	48
W-135	NE	NE	NE	NE	NE	NE	NE	NE	30	26
W-136	NE	NE	NE	NE	NE	NE	NE	NE	230	230
W-137	NE	NE	NE	NE	NE	NE	NE	NE	350	300
W-139	NE	NE	NE	NE	NE	NE	NE	NE	89	74
W-140	NE	NE	NE	NE	NE	NE	NE	NE	56	36
W-141	NE	NE	NE	NE	NE	NE	NE	NE	90	150
W-1004	NE	14	15	26	18	27	24	7.2	3.6	3.2
W-1005	NE	100	62	80	59	95	86	22	15	12
W-1021	NE	NE	NE	57	32	57	46	17	11	16
W-1022	NE	NE	NE	13	ND	20	21	7.6	4.8	12
W-1041	NE	NE	NE	16	ND	ND	ND	ND	ND	ND

Appendix B (Continued)

WELL NO.	SAMPLING (ug/L) 6/85	12/85	4/86	12/86	2/87	5/87	9/87	10/87	2/88	6/88
Vinyl Chloride										
W-10	ND	NS	NS	NS	NS	NS	NS	810	NS	400
W-11	ND	NS	NS	NS	NS	NS	NS	ND	NS	13
W-33S	ND	NS	NS	2.9	10	11	5.1	ND	ND	4.9
W-54	NS	NS	NS	1200	1224	190	17	40	5	ND
W-72	NE	NE	NE	NS	NS	41	ND	ND	ND	ND

ND = Analyte not detected or sample was diluted to quantify high concentrations of TCE and other analytes.

NE = Well not in existence at time of sampling

NS = Well not part of the sampling program at time of sampled or well was not sampled for a particular analyte.

Appendix C: Hydrocarbon Concentrations In Soil Samples Wright-Patterson AFB OH, Fire Training Area 5

SAMPLE	DEPTH (FT)	PPM JP-4 IN SOIL
SB1A	10-12	2000
SB1B	12-14	6400
SB1C	14-16	2000
SB1D	16-18	200
SB1E	18-20	640
SB2A	11-13	2300
SB2B	13-15	60
SB2C	15-17	220
SB2D	17-19	40
SB2E	19-21	400
SB2E (DUP)	19-21	1060
SB3A	10-12	2900
SB3B	12-14	920
SB3C	14-16	160
SB3D	16-18	<10
SB3E	18-20	<10
SB4A	10-12	1400
SB4B	12-14	6000
SB4C	14-16	2700
SB4D	16-18	360
SB4E	18-20	100
SB4E (DUP)	18-20	40
SB5A	10-12	1400
SB5B	12-14	100
SB5C	14-16	80
SB5D	16-18	460
SB5E	18-20	160
SB6A	10-12	1240
SB6B	12-14	620
SB6C	14-16	<10
SB6D	16-18	<10
SB6E	18-20	<10
SB6E (DUP)	18-20	<10

Appendix D: Water and Fuel Level Data
Wright-Patterson AFB OH,
Fire Training Area 5

Well No. 1

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	791.19	791.50	0.31
18 Jan 88	791.13	791.42	0.29
22 Jan 88	791.32	791.70	0.38
18 Feb 88	791.96	792.04	0.08
1 Mar 88	791.92	791.93	0.01
8 Mar 88	792.30	792.30	0.00
18 Mar 88	791.86	791.86	trace
25 Mar 88	791.88	791.88	0.00
7 Apr 88	792.31	792.31	0.00
8 Apr 88	792.34	792.34	trace
15 Apr 88	791.88	791.89	0.01
25 Apr 88	791.70	791.70	0.00
5 May 88	791.46	791.48	0.02
10 May 88	791.41	791.42	0.01
13 May 88	791.56	791.56	0.00
17 May 88	791.45	791.45	0.00
20 May 88	791.37	791.37	0.00
26 May 88	791.43	791.43	0.00
1 Jun 88	791.24	791.27	0.03
10 Jun 88	791.45	791.45	0.00
17 Jun 88	791.27	791.27	0.00
22 Jun 88	791.19	791.19	trace
30 Jun 88	791.15	791.15	trace

Well No. 2

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	790.30	791.47	1.17
18 Jan 88	790.14	791.39	1.25
22 Jan 88	790.49	791.64	1.15
18 Feb 88	791.46	792.21	0.75
1 Mar 88	791.84	791.91	0.07
8 Mar 88	792.22	792.29	0.07
18 Mar 88	791.84	791.89	0.05
25 Mar 88	791.81	791.84	0.03

Appendix D (Continued)

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Apr 88	792.18	792.21	0.03
8 Apr 88	792.32	792.39	0.07
15 Apr 88	791.90	791.92	0.02
25 Apr 88	791.64	791.66	0.02
5 May 88	791.55	791.55	trace
10 May 88	791.46	791.48	0.02
13 May 88	791.51	791.51	trace
17 May 88	791.49	791.49	trace
20 May 88	791.45	791.45	trace
26 May 88	791.45	791.45	trace
1 Jun 88	791.36	791.36	trace
10 Jun 88	791.31	791.32	0.01
17 Jun 88	791.29	791.29	trace
22 Jun 88	791.23	791.23	trace
30 Jun 88	791.17	791.17	trace

Well No. 3

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	790.68	791.18	0.50
18 Jan 88	790.45	791.14	0.69
22 Jan 88	790.61	791.41	0.80
18 Feb 88	791.51	791.53	0.02
1 Mar 88	791.58	791.59	0.01
8 Mar 88	791.78	791.81	0.03
18 Mar 88	791.46	791.47	0.01
25 Mar 88	791.36	791.36	trace
7 Apr 88	792.29	792.29	trace
8 Apr 88	791.88	791.89	0.01
15 Apr 88	791.39	791.41	0.02
25 Apr 88	791.16	791.17	0.01
5 May 88	791.08	791.09	0.01
10 May 88	790.97	790.99	0.02
13 May 88	790.89	791.04	0.15
17 May 88	790.43	791.04	0.61
20 May 88	790.39	791.00	0.61
26 May 88	790.55	790.90	0.35
1 Jun 88	790.72	790.72	trace
10 Jun 88	790.77	790.77	trace
17 Jun 88	790.76	790.76	trace
22 Jun 88	790.64	790.64	trace

Appendix D (Continued)

Well No. 4

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
30 Jun 88	790.67	790.67	trace
7 Jan 88	790.60	791.25	0.65
18 Jan 88	790.46	791.17	0.71
22 Jan 88	790.67	791.42	0.75
18 Feb 88	791.57	791.58	0.01
1 Mar 88	791.64	791.64	trace
8 Mar 88	791.93	791.93	0.00
18 Mar 88	791.52	791.52	0.00
25 Mar 88	791.43	791.43	trace
7 Apr 88	792.36	792.36	0.00
8 Apr 88	791.96	791.96	0.00
15 Apr 88	791.47	791.47	trace
25 Apr 88	791.23	791.23	0.00
5 May 88	791.16	791.16	trace
10 May 88	791.06	791.06	trace
13 May 88	791.06	791.06	trace
17 May 88	790.98	790.98	trace
20 May 88	790.95	790.95	trace
26 May 88	790.89	790.89	trace
1 Jun 88	790.76	790.78	0.02
10 Jun 88	790.53	790.90	0.37
17 Jun 88	790.64	790.86	0.22
22 Jun 88	790.48	790.74	0.26
30 Jun 88	790.42	790.79	0.37

Well No. 5A

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	792.85	792.89	0.04
18 Jan 88	792.76	792.81	0.05
22 Jan 88	793.04	793.08	0.04
18 Feb 88	791.79	791.81	0.02
1 Mar 88	791.78	791.78	trace
8 Mar 88	792.15	792.15	0.00
18 Mar 88	791.70	791.70	trace
25 Mar 88	791.59	791.60	0.01
7 Apr 88	792.36	792.36	0.00
8 Apr 88	792.14	792.14	0.00
15 Apr 88	791.67	791.67	trace

Appendix D (Continued)

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
25 Apr 88	791.44	791.45	0.01
5 May 88	791.36	791.36	trace
10 May 88	791.27	791.27	trace
13 May 88	791.27	791.27	trace
17 May 88	791.22	791.22	0.00
20 May 88	791.19	791.19	0.00
26 May 88	791.15	791.15	0.00
1 Jun 88	791.03	791.03	0.00
10 Jun 88	791.04	791.04	trace
17 Jun 88	791.03	791.03	0.00
22 Jun 88	790.93	790.93	0.00
30 Jun 88	790.93	790.93	trace

Well No. 6

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	790.50	791.27	0.77
18 Jan 88	790.33	791.19	0.86
22 Jan 88	790.69	791.39	0.70
18 Feb 88	791.38	791.42	0.04
1 Mar 88	791.55	791.55	trace
8 Mar 88	791.93	791.93	0.00
18 Mar 88	791.44	791.44	0.00
25 Mar 88	791.33	791.33	trace
7 Apr 88	792.24	792.24	0.00
8 Apr 88	791.86	791.86	trace
15 Apr 88	791.38	791.38	trace
25 Apr 88	791.13	791.14	0.01
5 May 88	790.95	791.08	0.13
10 May 88	790.84	790.99	0.15
13 May 88	790.86	791.01	0.15
17 May 88	790.79	790.91	0.12
20 May 88	790.79	790.91	0.12
26 May 88	790.68	790.83	0.15
1 Jun 88	790.54	790.72	0.18
10 Jun 88	790.70	790.74	0.04
17 Jun 88	790.65	790.74	0.09
22 Jun 88	790.60	790.61	0.01
30 Jun 88	790.65	790.66	0.01

Appendix D (Continued)

Well No. 7

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	------	------	----
18 Jan 88	------	------	----
22 Jan 88	------	------	----
18 Feb 88	791.83	791.83	0.00
1 Mar 88	791.75	791.75	0.00
8 Mar 88	792.15	792.15	0.00
18 Mar 88	791.70	791.70	0.00
25 Mar 88	791.63	791.63	0.00
7 Apr 88	792.25	792.25	0.00
8 Apr 88	792.16	792.16	0.00
15 Apr 88	791.76	791.76	0.00
25 Apr 88	791.43	791.43	0.00
5 May 88	791.36	791.36	0.00
10 May 88	791.26	791.26	0.00
13 May 88	791.29	791.29	0.00
17 May 88	791.25	791.25	0.00
20 May 88	791.20	791.20	0.00
26 May 88	791.18	791.18	0.00
1 Jun 88	791.08	791.08	0.00
10 Jun 88	791.07	791.07	0.00
17 Jun 88	791.08	791.08	0.00
22 Jun 88	790.99	790.99	0.00
30 Jun 88	791.00	791.00	0.00

Well No. RW-A

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	790.63	790.90	0.27
18 Jan 88	790.46	790.91	0.45
22 Jan 88	790.67	790.71	0.04
18 Feb 88	790.63	790.69	0.06
1 Mar 88	791.15	791.16	0.01
8 Mar 88	791.54	791.55	0.01
18 Mar 88	790.88	790.89	0.01
25 Mar 88	790.71	790.73	0.02
7 Apr 88	792.24	792.30	0.06
8 Apr 88	791.11	791.19	0.08
15 Apr 88	790.62	790.69	0.07

Appendix D (Continued)

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
25 Apr 88	790.19	790.46	0.27
5 May 88	790.20	790.43	0.23
10 May 88	790.06	790.35	0.29
13 May 88	789.99	790.38	0.39
17 May 88	789.82	790.18	0.36
20 May 88	789.85	790.12	0.27
26 May 88	789.69	790.02	0.33
1 Jun 88	789.62	789.88	0.26
10 Jun 88	789.86	790.02	0.16
17 Jun 88	789.82	790.02	0.20
22 Jun 88	789.68	789.84	0.16
30 Jun 88	789.71	789.89	0.18

Well No. RW-B

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	------	------	----
18 Jan 88	------	------	----
22 Jan 88	------	------	----
18 Feb 88	790.60	790.81	0.21
1 Mar 88	790.90	791.12	0.22
8 Mar 88	791.23	791.46	0.23
18 Mar 88	790.84	791.04	0.20
25 Mar 88	790.68	790.95	0.27
7 Apr 88	792.31	792.38	0.07
8 Apr 88	791.24	791.42	0.18
15 Apr 88	790.84	791.01	0.17
25 Apr 88	790.69	790.91	0.22
5 May 88	790.70	790.86	0.16
10 May 88	790.35	790.62	0.27
13 May 88	790.29	790.63	0.34
17 May 88	790.27	790.46	0.19
20 May 88	790.41	790.58	0.17
26 May 88	790.15	790.49	0.34
1 Jun 88	789.94	790.12	0.18
10 Jun 88	790.26	790.40	0.14
17 Jun 88	790.18	790.38	0.20
22 Jun 88	789.94	790.10	0.16
30 Jun 88	790.06	790.22	0.16

Appendix D (Continued)

Well No. RW-C

Date	Water Elev. (ft)	Fuel Elev. (ft)	Fuel Thickness (ft)
7 Jan 88	------	------	----
18 Jan 88	------	------	----
22 Jan 88	------	------	----
18 Feb 88	790.22	790.43	0.21
1 Mar 88	790.80	791.01	0.21
8 Mar 88	791.11	791.45	0.34
18 Mar 88	790.61	790.85	0.24
25 Mar 88	790.30	790.58	0.28
7 Apr 88	792.15	792.26	0.11
8 Apr 88	790.95	791.10	0.15
15 Apr 88	790.37	790.62	0.25
25 Apr 88	790.15	790.34	0.19
5 May 88	790.15	790.30	0.15
10 May 88	790.03	790.17	0.14
13 May 88	790.00	790.15	0.15
17 May 88	789.67	789.90	0.23
20 May 88	789.65	789.83	0.18
26 May 88	789.39	789.67	0.28
1 Jun 88	788.87	789.76	0.89
10 Jun 88	789.66	789.78	0.12
17 Jun 88	789.61	789.76	0.15
22 Jun 88	789.48	789.61	0.13
30 Jun 88	789.53	789.68	0.15

Appendix E: Wright-Patterson AFB, Biological Nutrient and Hydrocarbon Utilizers Count

WELL 1

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	144	120
02/18/18	1120	1280
03/08/88	30400	26400
03/16/88	57600	28000
03/23/88	8000	42000
03/30/88	9900	12800
04/07/88	2160	20400
04/25/88	38600	320
05/12/88	2160	1840
05/26/88	7600	13600
06/08/88	5200	5200

WELL 2

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	260	160
02/18/18	500	1320
03/08/88	1720	6800
03/16/88	75200	22400
03/23/88	560	2040
03/30/88	5100	12400
04/07/88	39200	48200
04/25/88	2000	120
05/12/88	2240	2760
05/26/88	9200	18000
06/08/88	6000	2160

WELL 3

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	680	0

Appendix E (continued)

WELL 3 (continued)

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
02/18/18	1100	5600
03/08/88	880	1120
03/16/88	400	60
03/23/88	54	480
03/30/88	2120	280
04/07/88	2640	6200
04/25/88	1710	100
05/12/88	3400	1280
05/26/88	1360	2080
06/08/88	276	20

WELL 4

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	180	120
02/18/18	680	360
03/08/88	3200	7600
03/16/88	580	320
03/23/88	1760	12000
03/30/88	2240	1920
04/07/88	5400	14200
04/25/88	2800	140
05/12/88	3600	3360
05/26/88	3800	4280
06/08/88	2800	2800

WELL 5

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	40000	7200
02/18/18	18000	1160
03/08/88	720	1280
03/16/88	920	360
03/23/88	110	5020

Appendix E (continued)

WELL 5 (continued)

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
Ø3/3Ø/88	46ØØØ	526Ø
Ø4/Ø7/88	56ØØ	38ØØØ
Ø4/25/88	65Ø	6Ø
Ø5/12/88	17Ø	12Ø
Ø5/26/88	34Ø	68Ø
Ø6/Ø8/88	9Ø	4Ø

WELL 6

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
Ø1/27/88	1Ø4Ø	56Ø
Ø2/18/18	38ØØ	84ØØ
Ø3/Ø8/88	28ØØØ	256ØØ
Ø3/16/88	34ØØØ	128ØØ
Ø3/23/88	76ØØ	176ØØ
Ø3/3Ø/88	9ØØØØ	232ØØ
Ø4/Ø7/88	124ØØØ	428ØØ
Ø4/25/88	31ØØØ	124ØØ
Ø5/12/88	68ØØ	116ØØ
Ø5/26/88	92ØØ	64ØØ
Ø6/Ø8/88	212ØØ	12ØØØ

WELL 7

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
Ø1/27/88	56ØØ	56ØØ
Ø2/18/18	134Ø	1Ø8ØØ
Ø3/Ø8/88	192Ø	1Ø[illegible]Ø
Ø3/16/88	2Ø8Ø	136Ø
Ø3/23/88	36Ø	28ØØ
Ø3/3Ø/88	51Ø	28Ø
Ø4/Ø7/88	248Ø	464Ø
Ø4/25/88	336Ø	32Ø
Ø5/12/88	14Ø	156Ø

Appendix E (continued)

WELL 7 (continued)

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
05/26/88	1000	4280
06/08/88	500	2720

WELL RW-A

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	420	0
02/18/18	208	240
03/08/88	80	80
03/30/88	27	0
04/07/88	176	80
04/25/88	59	40
05/12/88	7	20
05/26/88	17	60
06/08/88	26	40

WELL RW-B

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	-	-
02/18/18	-	-
04/25/88	216	0
05/12/88	52	200
05/26/88	64	100
06/08/88	120	80

WELL RW-A

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
01/27/88	-	-
02/18/18	-	-

Appendix E (continued)

WELL RW-A

DATE	TOTAL COUNT NUTRIENT AGAR	HYDROCARBON UTILIZERS MINERAL AGAR
04/25/88	440	20
05/12/88	18	220
05/26/88	128	120
06/08/88	76	40

Appendix F: Wurtsmith AFB Total Water Pumped Monthly and TCE Contaminant Level

Total Water Pumped Per Month (Thousand Gallons)

Date	AF-1	AF-3	AF-55	AF-56	AF-57	P-1	P-2	P-3	P-4
Oct 78	7878	8469	2092	2092	2092	---	---	---	---
Mar 79	8269	4887	1517	1934	3571	---	---	---	---
Apr 79	7608	4071	1879	1879	3341	---	---	---	---
Jul 79	9025	7186	2009	1401	998	---	---	---	---
Oct 79	7539	4507	2009	2009	3514	---	---	---	---
Jan 80	7702	2739	1941	----	3492	---	---	---	---
Apr 80	8750	3	1847	----	3341	---	---	---	---
Jul 80	8642	----	1454	----	1970	---	---	---	---
Oct 80	720	7957	962	793	135	---	---	---	---
Jan 81	----	8208	341	----	389	---	---	---	---
Apr 81	----	8208	263	----	315	---	---	---	---
Jul 81	246	2806	----	----	----	---	---	---	---
Oct 81	297	2748	----	----	----	---	---	---	---
Jan 82	5583	6842	----	----	----	---	---	---	---
May 82	----	630	----	----	----	4276	802	420	3386
Aug 82	1500	----	----	----	----	9338	9368	9367	4856
Oct 82	8216	----	----	----	----	8167	10543	9079	8085
Jan 83	----	----	----	----	----	3655	4085	3639	3589
Apr 83	----	----	----	----	----	6961	10206	9462	7359
Jul 83	----	----	----	----	----	5387	7743	10681	2949
Oct 83	----	----	----	----	----	5930	7346	10863	135
Jan 84	----	----	----	----	----	8123	----	----	9613
Apr 84	12514	----	----	----	----	6995	823	----	6771
Jul 84	10466	----	----	----	----	5669	3664	----	5589
Oct 84	7027	----	----	----	----	2570	----	3270	3260
Jan 85	14995	----	----	----	----	1317	4927	399	4899
Apr 85	1450	----	----	----	----	2241	7415	6786	1708
Jul 85	7547	----	----	----	----	5487	1959	7638	3067
Oct 85	7694	----	----	----	----	----	----	6163	1246
Jan 86	7808	----	----	----	----	2130	4135	4655	4468
Apr 86	7497	----	----	----	----	2716	2570	3721	4199
Jul 86	7384	----	----	----	----	6202	3612	7650	5280
Oct 86	8384	----	----	----	----	53	5662	----	1449
Jan 87	9205	----	----	----	----	2356	----	6903	----
Apr 87	8392	----	----	----	----	4366	6387	6800	----
Jun 87	8712	----	----	----	----	3209	1934	3947	2452
Jul 87	8939	----	----	----	----	1557	2184	3579	2579
Aug 87	9321	----	----	----	----	1854	5644	2507	3308
Sep 87	8832	----	----	----	----	5558	5559	3310	3588
Oct 87	7097	----	----	----	----	----	6574	390	4452
Nov 87	5595	----	----	----	----	----	5654	----	4099

Appendix F (continued)

Total Water Pumped Per Month (Thousand Gallons)

Date	AF-1	AF-3	AF-55	AF-56	AF-57	P-1	P-2	P-3	P-4
Dec 87	5798	----	----	----	----	----	6854	----	4494
Jan 88	4730	----	----	----	----	----	2032	2597	5259
Feb 88	6476	----	----	----	----	----	2362	----	6082
Mar 88	8386	----	----	----	----	----	7425	5738	6364
Apr 88	4092	----	----	----	----	1207	4589	5310	4065
May 88	3564	----	----	----	----	3152	2628	3469	2203
Jun 88	6642	----	----	----	----	6545	5100	7490	5367

Total TCE Pumped Per Month (ug/L)

Date	AF-1	AF-3	AF-55	AF-56	AF-57	P-1	P-2	P-3	P-4
Oct 78	724.6	2200.6	82.7	864.7	3307	---	---	---	---
Mar 79	507.0	2144.0	87.7	1644.7	1128.3	---	---	---	---
Apr 79	452.8	2333.0	52.0	1794.7	1890.0	---	---	---	---
Jul 79	418.2	2613.6	187.8	----	1715.4	---	---	---	---
Oct 79	234.2	2127.3	43.3	2277.8	826.3	---	---	---	---
Jan 80	182.0	2355.0	107.3	----	----	---	---	---	---
Apr 80	89.1	----	54.4	----	754.0	---	---	---	---
Jul 80	70.9	----	55.1	----	876.0	---	---	---	---
Oct 80	63.5	1660.5	55.1	----	1128.3	---	---	---	---
Jan 81	----	1351.2	21.9	----	1045.0	---	---	---	---
Apr 81	----	1014.0	----	----	988.0	---	---	---	---
Jul 81	13.1	1438.0	----	5.4	551.1	---	---	---	---
Oct 81	34.0	----	----	----	----	---	1062	1027	971
Jan 82	20.0	1196.0	----	----	----	---	---	---	---
May 82	34.0	----	----	----	----	---	1062	1027	971
Aug 82	24.8	247.0	----	----	----	---	832	557	462
Oct 82	44.1	----	----	----	----	---	517	358	274
Jan 83	----	----	----	----	----	---	452	349	232
Apr 83	----	----	----	----	----	---	338	232	156
Jul 83	----	----	----	----	----	---	342	297	317
Oct 83	----	----	----	----	----	---	294	219	---
Jan 84	----	----	----	----	----	---	---	---	300
Apr 84	54.0	----	----	----	----	---	266	243	175
Jul 84	50.0	----	----	----	----	---	237	---	276
Oct 84	10.0	----	----	----	----	---	---	127	118
Jan 85	52.5	----	----	----	----	---	213	197	192
Apr 85	25.9	----	----	----	----	---	85	131	123
Jul 85	33.4	----	----	----	----	---	191	159	318
Oct 85	42.9	----	----	----	----	---	---	181	172
Jan 86	30.0	----	----	----	----	---	135	133	177
Apr 86	25.9	----	----	----	----	---	136	206	303

Appendix F (continued)

Total TCE Pumped Per Month (ug/L)

Date	AF-1	AF-3	AF-55	AF-56	AF-57	P-1	P-2	P-3	P-4
Jul 86	26.2	----	----	----	----	---	160	163	519
Oct 86	26.9	----	----	----	----	---	---	120	---
Jan 87	28.0	----	----	----	----	---	---	61	81
Apr 87	26.1	----	----	----	----	---	142	131	---
Jun 87	37.4	----	----	----	----	---	97	88	---
Jul 87	27.0	----	----	----	----	---	127	65	406
Aug 87	23.1	----	----	----	----	---	94	71	400
Sep 87	25.8	----	----	----	----	---	123	79	420
Oct 87	20.7	----	----	----	----	---	104	66	298
Nov 87	25.2	----	----	----	----	---	109	133	116
Dec 87	21.0	----	----	----	----	---	102	177	157
Jan 88	30.6	----	----	----	----	---	84	203	227
Feb 88	23.7	----	----	----	----	---	107	120	184
Mar 88	29.5	----	----	----	----	---	91	107	160
Apr 88	32.8	----	----	----	----	---	61	86	171
May 88	20.0	----	----	----	----	---	92	72	198
Jun 88	21.4	----	----	----	----	---	77	55	160

All data was extracted from monthly sampling logs and furnish by Mike Miklow, Environmental Coordinator Wurtsmith AFB.

Blanks mean that data is not available, either it was not sampled, the samples were broken in transit, or some other "lab accident" occurred.

Bibliography

1. Air Force Engineering and Service Center. Groundwater Contamination Response Guide. Tyndall Air Force Base FL, June 1983 (EST-TR-82-39).

2. American Water Works Assoc. "Underground Waste Disposal and Ground-Water Contamination," Journal of American Water Works Assoc, vol 52, no. 5, pp. 619-622 (1960).

3. Barrett, Bruce R. "Controlling the Entrance of toxic pollutants into U.S. Waters," Environmental Sciences and Technology, vol 12, pp. 154-162 (February 1978).

4. Biosystems Incorportated. "February Progress Report For Wright-Patterson AFB, Ohio", 2100 ConCord Road, Chester Township PA, February 1988.

5. Charbeneau, Randall J. "Calculation of Pollutant Removal During Groundwater Restoration With Adsorption and Ion Exchange," Water Resources Research, vol 18, no. 4, pp. 1117-1125 (August 1982).

6. Charbeneau, Randall J. "Groundwater Contaminant transport With Adsorption and Ion Exchange Chemistry: Method of Characteristics for the Case Without Dispersion," Water Resources Research, vol 17, no. 3, pp. 705-713 (June 1981).

7. CH2M Hill Southest, Incorporated. Installation Restoration Program Records Search for McClellan Air Force Base, California. Gainsville FL, July 1981 (AD-A124153).

8. Cummings, T. R. and F. R. Twenter. Assessment of Ground-Water Contamination at Wurtsmith Air Force Base, Michigan, 1982-85. United Stated Geological Survey Water-Resources Investigations Report 86-4188 (1986).

9. Dagan, G. "Stochastic Modeling of Groundwater Flow by Unconditional and Conditional Probabilities," Water Resources, vol 18, no. 5, p. 1571 (October 1982).

10. Department of the Air Force. Air Force Installation Restoration Program Management Guidance. Engineering and Service Center, Tyndall AFB FL, July 1985.

11. Dyksen, John E. and Alan F. Hess III. "Alternatives for Controlling Organics in Groundwater Supplies," Journal of the American Water Works Association, vol 74(8), pp. 394-403 (1982).

12. Edwards, R.E. and others. "Cleanup of Chemically Contaminated sites," Chemical Engineering, vol 90, pp. 78-81 (21 February 1983).

13. Elder, Vincent A. and others. "Organic Compounds Found Near Dump Sites in Niagara Falls, New York," The Journal of the American Chemical Society, vol 15, no. 10, pp. 1237-1242 (October 1981).

14. Elliott, Mike, Lieutenant. Telephone interview. Engineering and Services Center, Tyndall AFB FL, 15 April 1988.

15. Engineering-Science. Final Report Installation Restoration Program Phase II: Confirmation McClellan AFB, California. 125 West Huntington Drive, Arcadia CA, June 1983 (AD-A131364).

16. Fink, T. Patrick, Major. Telephone interview. Policy and Assessment Branch, Environmental Division, USAF, Bolling AFB DC, 6 February 1988.

17. Hoeks, J. "Analytical Solutions for Transport of Conservative and Nonconservative Contaminants in Groundwater Systems," Waste, Air and Soil Pollution, vol 16, pp. 339-350 (1981).

18. Hokanson, Colonel Lawrence D. "1988 Technology Update-Bioremediation of Fuel Spills" USAF, Director Engineering and Services Laboratory, Tyndall AFB FL, 5 July 1988.

19. Josephson, J. "Restoration of Aquifers," Environmental Science and Technology, vol 17(6), pp. 347A-350A (1983).

20. Keely, C.D. and others. "Optimizing Recovery of Contaminant Residuals by Pulsed Operation of Hydraulically Dependent Remediations," Department of Environmental Science and Engineering, Oregon Graduate Center, Beaverton OR.

21. Kobayashi, Hester and Bruce E. Rittmann. "Microbial Removal of Hazardous organic compounds," Environmental Science and Technology, vol 16, pp. 170A-181A (March 1982).

22. Kraybill, Herman F. "Carcinogenesis of Synthetic Organic Chemicals in Drinking Water," Journal of the American Water Works Association, vol 73, pp. 370-372 (1981).

23. Love, Thomas O. Jr. and Richard G. Eilers. "Treatment of Drinking Water Containing Tirchloroethylene and Related Industrial Solvents," Journal of the American Water Works Association, vol 74(8), pp. 413-425 (1985).

24. Mackay, Douglas M. and others. "Transport of Organic Contaminants in Groundwater," Journal of Environmental Science and Technology, vol 19, no. 5, pp. 384-392 (1985).

25. Madden, Michael P. Installation Restoration and Hazardous Waste Control Technologies. Report Number AMXTH-TE-CR-88010. The National Institute for Petroleum and Energy Research, Bartlesville OK, January 1988.

26. Mangan, Charles M. and others. Installation Restoration Program Phase I: Records Search Wright-Patterson AFB, Ohio. Engineering-Science 125 West Huntighton Drive, Arcadia CA, February 1982 (AD-A123316).

27. Mauch, T.H. "Chemicals: How Many Are There?" Science, vol 199, p. 162 (1878).

28. Miller, S. "The Persistent PCB Problem," Environmental Science and Technology, vol 16, pp. 98-101 (1982).

29. Montgomery, James M. Installation Restoration Program Phase IV-A Feasibility Study Notherest Disposal Area Upper Aquifer Remediation, George Air Force Base San Bernardino County, California. Consulting Engineers Incorporated, Pasadena CA. April 1988.

30. Nagorka, Jennifer. "Tackling Toxics With Microbes," Engineering at Stanford, pp. 5-6 (January 1988).

31. Olivieri, Adam W. and others. "Groundwater Contamination Site Ranking Methodology," Journal of Environmental Engineering, vol 112, no. 4, p. 757 (August 1986).

32. Page, William G. "Comparison of Groundwater and Surface water for Patterns and Levels of Contamination by Toxic Substances," Environmental Science and Technology, vol 15(12), pp. 1475-1481 (1981).

33. Pawley, John D. "Groundwater Pollution: A Case Study," Journal of the American Water Works Association, vol 74, p. 405 (1982).

34. Pinder, George F. "Groundwater Contaminant Transport Modeling," Environmental Science and Technology, vol 18, no. 4, 108A-114A (1984).

35. Radian Corporation. Installation Restoration Program Phase I: Records Search Wurtsmith AFB, Michigan. 7655 Old Springhouse Road, McLean VA. April 1985 (AD-A158249).

36. Roberts, Paul V. and others. "Movement of Organic Contaminants in groundwater: Implications for Water supply," Journal of the American Water Works Association, vol 74(8), pp. 408-412 (1982).

37. Robin, Jerry. "Area D Interim Remedial Measure" McClellan AFB CA, 1988

38. Schwarzenbach, R.J. and others. "Behavior of Organic Compounds during Infiltration of River Water to Groundwater. Field Studies," Environmental and Science Technology, vol 17, pp. 472-479 (1983).

39. Shackelford, Walter M. and David M. Cline. "Organic Compounds in Water," Environmental Science and Technology, vol 20, no. 7: 653-657 (1986).

40. Sink, Scott D. Productivity Management: Planning, Measurement and Evaluation, Control and Improvement. John Wiley and Sons, Incorporated, 1985.

41. Stuermer, Daniel H. and others. "Organic Contaminants in Groundwater Near An Underground Coal Gasification Site in Northeastern Wyoming," Environment Science and Technology vol 16, no. 9, pp. 582-586 (1982).

42. Todd, D.K. and D.E.O. Mcnulty. Polluted Groundwater: A Review of the Significant Literature, Water Information Center, Inc., 7 High Street, Hunington NY, 1976.

43. United States Environmental Protection Agency. Handbook: Remedial Action at Waste Disposal Sites (Revised). Washington: Office of Emergency and Remedial Response, October 1985 (EPA/625/6-85/006).

44. United States General Accounting Office. Superfund: Cost Growth on Remedial Construction Activities. GAO/RCED-88-69, February 1988.

45. United States Occupational and Environmental Health Laboratory (OEHL). Installation Restoration Program Final Report: Phase II Stage I Study Wright-Patterson AFB, Dayton, OH. September 1985 (AD-A159573).

46. Weston, Roy F. and others Installation Restoration Program Phase II: Confirmation/Quantification Stage I - Final Report For Wright-Patterson Air Force Base Dayton, Ohio. Contract No. F33615-80-D-4006. Roy F. Weston Incorporate, 1 August 1985 (AD-A159573).

47. Wood, Paul R. and Jack DeMarco. "Treatment of Groundwater With Granular Activated Carbon," Journal of the American Water Works Association, vol 69(11), pp. 674-678 (1979).

48. Zoltek J. Jr. and J.F.K. Earle. Feasibility Study: Liquid-liquid Extraction (LLX) as a Cleanup Process for Groundwater, Soils and CBW Agents. Air Force Engineering and Services Lab, Engineering and Services Center, Tyndall Air Force Base FL, January 1985 (ESL-TR-84-44).

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Block 19. Abstract

This thesis is an attempt to determine the effectiveness of the Air Force's use of pump-and-treat technology to remediate groundwater contamination. The study is divided into four major sections: 1) literature survey of groundwater contamination problems and remediation technology. 2) identification of bases where pump-and-treat technology has been employed. 3) collection of quantitative data from bases for analysis. 4) analysis of data and recommendations.

Data was obtained from three Air Force installations, McClellan AFB, Wright-Patterson AFB, and Wurtsmith AFB. During remediation, contaminants in most cases show a significant decrease in concentration though levels are still well above regulatory agency requirements. Furthermore, it was found that the inconsistent timing of data sampling and the lack of standardized data storage procedures prevents reliable determination of remediation effectiveness.

Conclusions of this study are that a standardized data collection system be created, under direct supervision of an air staff office, and that a centralized procedure be identified for evaluating the effectiveness of pump-and-treat programs. While the current remediation programs using pump-and-treat initially show large reductions in contaminant concentrations, continued application of this method produces only slight incremental improvements. It appears that decades may be required to meet existing regulatory limits.